(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 674 210 B1

(12) EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention of the grant of the patent:
24.01.2001 Bulletin 2001/04

(51) Int Cl.7: G02F 1/225, G02F 1/313, G02F 1/03, H04B 10/18

(21) Application number: 95109629.6

(22) Date of filing: 14.03.1990

(54) Optical modulator

Optischer Modulator

Modulateur optique

(84) Designated Contracting States:
DE FR GB

(30) Priority: 14.03.1989 JP 5961789
14.03.1989 JP 6153489

(43) Date of publication of application:
27.09.1995 Bulletin 1995/39

(62) Document number(s) of the earlier application(s) in accordance with Art. 76 EPC:
90104811.6 / 0 387 832

(73) Proprietor: FUJITSU LIMITED
Kawasaki-shi, Kanagawa 211 (JP)

(72) Inventors:
- Hamano, Hiroshi
Kawasaki-shi, Kanagawa 213 (JP)
- Amemiya, Izumi
Yokohama-shi, Kanagawa 222 (JP)
- Nishimoto, Hiroshi
Kanagawa 228 (JP)
- Namiki, Takefumi
Ebina-shi, Kanagawa 243-04 (JP)
- Yokota, Izumi
Tama-ku, Kawasaki-shi, Kanagawa 214 (JP)
- Okiyama, Tadashi
Yokohama-shi, Kanagawa 227 (JP)
- Seino, Minoru
Atsugi-shi, Kanagawa 243 (JP)

(74) Representative: Lehn, Werner, Dipl.-Ing. et al
Hoffmann Eitle,
Patent- und Rechtsanwälte,
Arabellastrasse 4
81925 München (DE)

(56) References cited:
EP-A- 0 207 800 US-A- 4 768 848

- PATENT ABSTRACTS OF JAPAN vol. 12, no. 66 (P-671) 27 February 1988 & JP-A-62 206 520 (NEC)
- JOURNAL OF LIGHTWAVE TECHNOLOGY., vol.LT-3, no.4, August 1985, NEW YORK US pages 800 - 805 T.L. KOCH AND R.C. ALFERNESS 'Dispersion Compensation by Active Predistorded Signal Synthesis'

EP 0 674 210 B1

Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to an optical modulator used in a transmission apparatus for transmitting high speed digital signals in an optical communication system using optical fibers as a transmission channel.

[0002] In recent years, optical communication systems using optical signals as the medium of communication have rapidly been put into use. The optical modulators for producing the optical signals in the optical communication systems are extremely important devices. The present invention refers to such optical modulators, in particular external modulation type optical modulators.

2. Description of the Related Art

[0003] In the conventional direct modulation type optical modulators, when the modulation speed became large, so-called frequency chirping occurred, resulting in deterioration of the high speed characteristics. Frequency chirping is the shift in the wavelength of the light during the rise and fall of the light signal with each such rise and fall. Frequency chirping causes waveform deterioration in the light signal received in the receiving system through the optical fiber due to optical fiber wavelength dispersion. Therefore, in a high speed optical communication system wherein a high speed light modulation of several Gbps is required, it is not possible to use a direct modulation type optical modulator.

[0004] One known type of external modulation type optical modulator is a Mach-Zehnder interferometer type modulator, which will be explained later. Such a Mach-Zehnder interferometer type modulator has the smallest spread of the spectrum and therefore is able to avoid the waveform deterioration at the receiver caused by the effects of wavelength dispersion of the fiber. That is, in such a Mach-Zehnder interferometer type modulator, the phases of the light propagating through two optical waveguides are modulated in opposite directions by the same magnitude for modulation free from frequency chirping and it is thus possible to reduce the spectral spread to the spread of the modulation side band, by the Fourier component of the modulation waveform. Note that a known reference relating to an optical modulator of this type is F. Koyama et. al., JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 6, No. 1, January 1988, IEEE, pp. 87 to 93.

[0005] There are, however, the following problems in the conventional Mach-Zehnder interferometer type modulator.

[0006] First, while there is a desire to make the modulation driving circuit of the optical modulator by a semiconductor integrated circuit (IC) and thus reduce the size, it is not easy to make the modulation driving circuit by an IC chip. The reason is that the conventional Mach-Zehnder interferometer type modulator requires a high voltage of -5 V to -8 V and it is difficult to manufacture an IC able to withstand such a high voltage.

[0007] Second, while there is a desire to reduce the offset of the optical modulator as much as possible, it is not easy to reduce the offset. Here, "offset" means the offset in the modulation driving voltage and deviation in various characteristics accompanying temperature fluctuations.

[0008] Third, it is not possible to use an optical modulator for a long distance optical communication system operating at a high transmission speed of over several Gbps. This is due to the so-called wavelength dispersion in the optical fibers. That is, it has not been possible to meet the demand for constructing a high speed, long distance optical communication system using such general optical fibers producing large wavelength dispersions.

SUMMARY OF THE INVENTION

[0009] Therefore, the present invention has as its object the provision of an optical modulator which is able to satisfy each of the first to third desires mentioned above when so demanded by the designer of the optical communication system.

[0010] Accordingly, in a first aspect, the present invention provides an optical modulator comprising: a substrate; a Mach-Zehnder interferometer having: an input for incoming light, an output for outgoing light, and first and second optical waveguides formed in said substrate and coupled between said input and said output; and an electrode structure formed on said substrate and comprising at least one pair of separated electrodes associated with the first optical waveguide and having a driving voltage side electrode and a ground electrode connected thereto via a terminating resistance; the arrangement of said first and second optical waveguides and said electrode structure being asymmetric as between the first optical waveguide and the second optical waveguide for modulating the phase of light propagating through the first optical waveguide differently from the phase of light propagating through the second optical waveguide by means of the electrooptic effect, even when the same driving voltage is applied to an optional part of the electrode structure associated with the second optical waveguide as to said driving voltage side electrode of the pair of electrodes associated with the first optical waveguide.

[0011] In a second aspect, the present invention provides an optical modulator comprising: a substrate; a Mach-Zehnder interferometer having: an input for incoming light, an output for outgoing light, and first and second optical waveguides formed in said substrate and coupled between said input and said output; and an

electrode structure formed on said substrate and comprising: a first pair of separated electrodes associated with the first optical waveguide and having a first driving voltage side electrode and a first ground electrode connected thereto via a first terminating resistance, and a second pair of separated electrodes associated with the second optical waveguide and having a second driving voltage side electrode and a second ground electrode connected thereto via a second terminating resistance; the arrangement of said first and second optical waveguides and said electrode structure being symmetrical as between the first optical waveguide and the second optical waveguide; and driving means arranged to provide a first driving voltage to the first driving voltage side electrode and a second driving voltage different from the first driving voltage to the second driving voltage side electrode for modulating the phase of light propagating through the first optical waveguide differently from the phase of light propagating through the second optical waveguide by means of the electrooptic effect.

[0012] In a third aspect, the present invention provides a method of modulating light comprising: providing an optical modulator comprising: a substrate; a Mach-Zehnder interferometer having: an input for incoming light, an output for outgoing light, and first and second optical waveguides formed in said substrate and coupled between said input and said output; and an electrode structure formed on said substrate and comprising at least one pair of separated electrodes associated with the first optical waveguide and having a driving voltage side electrode and a ground electrode connected thereto via a terminating resistance; the arrangement of said first and second optical waveguides and said electrode structure being asymmetric as between the first optical waveguide and the second optical waveguide; applying light to said input of the Mach-Zehnder interferometer; and providing a driving voltage to the driving voltage side electrode of the pair of electrodes associated with the first optical waveguide, thereby modulating the phase of the applied light propagating through the first optical waveguide differently from the phase of the applied light propagating through the second optical waveguide by means of the electrooptic effect, even when applying the same driving voltage to an optional part of the electrode structure associated with the second optical waveguide.

[0013] In a fourth aspect, the present invention provides a method of modulating light comprising: providing an optical modulator comprising: a substrate; a Mach-Zehnder interferometer having: an input for incoming light, an output for outgoing light, and first and second optical waveguides formed in said substrate and coupled between said input and said output; and an electrode structure formed on said substrate and comprising: a first pair of separated electrodes associated with the first optical waveguide and having a first driving voltage side electrode and a first ground electrode connected thereto via a first terminating resistance, and a second pair of separated electrodes associated with the second optical waveguide and having a second driving voltage side electrode and a second ground electrode connected thereto via a second terminating resistance; the arrangement of said first and second optical waveguides and said electrode structure being symmetrical as between the first optical waveguide and the second optical waveguide; applying light to said input of the Mach-Zehnder interferometer; and providing a first driving voltage to the first driving voltage side electrode and a second driving voltage different from the first driving voltage to the second driving voltage side electrode, thereby modulating the phase of the applied light propagating through the first optical waveguide differently from the phase of the applied light propagating through the second optical waveguide by means of the electrooptic effect.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The above object and features of the present invention will be more apparent from the following description of the preferred embodiments with reference to the accompanying drawings, wherein:

FIG. 1 is a view schematically showing a first aspect of an optical modulator;
FIG. 2 is a view schematically showing a second aspect of the optical modulator;
FIG. 3 is a view showing a first prior art of an external modulator;
FIG. 4 is a graph for explaining an optical modulation operation in the first prior art;
FIG. 5 is a view of a second prior art of an external modulator;
FIG. 6 is a graph for explaining an optical modulation operation in the second prior art;
FIG. 7 is a block diagram of the principle and constitution of an optical modulator based on the present invention;
FIG. 8 is a view for explaining the principle of the first and later embodiments of the present invention;
FIG. 9 is a waveform diagram used for explaining FIG. 8;
FIG 10A is a view of the construction of a first embodiment of the present invention;
FIG. 10B is a view of an example of the circuit of the first and second driving units;
FIG. 11 is a time chart showing the operation of the first embodiment;
FIG. 12 is a plane view of a second embodiment of the present invention;
FIG. 13 is a plane view of a third embodiment of the present invention;
FIG. 14 is a sectional view of a fourth embodiment of the present invention;
FIG. 15 is a sectional view of a fifth embodiment of

the present invention;
FIG. 16 is a sectional view of a sixth embodiment of the present invention;
FIG. 17 is a plane view of a seventh embodiment of the present invention;
FIG. 18 is a plane view of an eighth embodiment of the present invention;
FIG. 19 is a graph of the results of a first calculation for explaining the improvement in the transmission characteristics of optical fibers according to the present invention; and
FIG. 20 is a graph of the results of a second calculation for explaining the improvement in the transmission characteristics of optical fibers according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0015] Before describing the embodiment of the present invention, the related art and the disadvantages therein will be described with reference to the related figures.

[0016] Figure 1 is a view of a first aspect of the optical modulator, which belongs to what are known as direct modulation type modulators. In the figure, reference numeral 11 is a light source, for example, a laser diode (LD), which is connected in series to a driving signal source 12. The optical modulator shown here applies direct modulation to the laser diode 11 to obtain modulated light MO.

[0017] In a direct modulation type optical modulator, when the modulation speed is large, as mentioned earlier, there is the disadvantage of the occurrence of frequency chirping, which forces the use of an external modulation type optical modulator.

[0018] Figure 2 is a schematic view of a second aspect of the optical modulator, which belongs to what are known as external modulation type modulators. In such external modulation type optical modulators, to eliminate the aforementioned frequency chirping, it is necessary to keep the laser diode constituting the light source 11 from blinking and make it transmit continuous light (direct current light) CO. Reference numeral 14 is a direct current source. The continuous light CO is modulated by the external modulator 13. The external modulator 13 is controlled by the driving voltage DV from the driving signal source 12 and transmits the modulated light MO. Therefore, it is possible for the receiving system to receive light signal with minimized waveform deterioration which is caused by frequency chirping and fiber wavelength dispersion.

[0019] Figure 3 is a view of a first prior art of an external modulator. This external modulator is a known Mach-Zehnder interferometer type modulator, which is constructed by a first optical waveguide 21 and second optical waveguide 22 formed in a substrate (for example, made of $LiNbO_3$), into the input terminals of which continuous light CO, split into two, is input, electrodes 23-1 and 23-2 formed above the same, the already mentioned driving signal source (signal input source) 12 which applies a driving voltage DV to one end of one electrode 23-1, and a terminating resistor R which is connected to the other end. The other electrode 23-2 is ground. To the input terminal is applied the continuous light CO. From the output side is taken out the modulated light MO.

[0020] Figure 4 is a graph for explaining the optical modulation operation in the first prior art. In the figure, the characteristic curve at the top left is that of the input driving voltage vs the optical output. If the pulse like driving voltage DV shown at the bottom left of the figure is input in accordance with that characteristic curve, the pulse like modulated light MO shown at the top right is obtained. Note that the characteristic curve is drawn facing left because a driving voltage of a negative voltage, for example, -5 V to -8 V, is assumed. For example, if a driving voltage of -5 V to -8 V is applied, an electrooptic effect is created by the electric field formed between the electrodes 23-1 and 23-2 through the substrate ($LiNbO_3$). Underneath the pair of electrodes 23-1 and 23-2, which form so-called traveling wave electrodes, the continuous light CO propagating through the first and second optical waveguides 21 and 22 deviate in phase 180° from each other. The composite lights at the output ends of the optical waveguides 21 and 22 cancel out each other and become zero ("0"). At this time, the modulated light MO becomes zero. Conversely, when the driving voltage DV is zero volt, the above-mentioned composite lights do not cancel each other out and there is a modulated light MO ("1").

[0021] Figure 5 is a view of a second prior art of an external modulator. This is substantially the same as the afore-mentioned first prior art (Fig. 3) except that a 3 dB optical coupler 35 is introduced into the optical output end. According to this second prior art, two differential modulated lights MO and $\overline{MO}$ are obtained.

[0022] Figure 6 is a graph for explaining an optical modulation operation in the second prior art. The difference from the above-mentioned first prior art is that the driving voltage DV spans two polarities from -2.5 V to -4 V and +2.5 V to +4 V. The advantage of the second prior art from the first prior art is that a complementary modulated light $\overline{MO}$ can be obtained.

[0023] There are three major problems with the first prior art and second prior art.

[0024] The first relates to the driving voltage DV, mentioned previously. That is, in the first prior art, a high voltage of -5 V to -8 V is required and it is difficult to make the driving signal source 12 with an actual circuit, especially with an integrated circuit (IC). Usually, the higher speed the operation required the withstand voltage of an IC becomes smaller. For example, even a GaAs IC has a withstand voltage of less than 3 V. Also the high voltage swing degrades the signal modulation speed. Going into further detail, if it is attempted to provide a

drive with a large voltage amplitude of -5 V to -8 V, first the effects of the stray capacitance will he large and therefore high speed operation will become difficult and, second, the terminating resistor R will be fixed (50 Ω) and therefore the drive will have to be with a large current amplitude, the stray capacitance of the driving signal source 12 will increase, and high speed operation will become even more difficult.

[0025] The second relates to the offset, also mentioned earlier. Annoying voltage drifts in the modulation characteristics and also the temperature fluctuations may arise because of this offset. The cause of this is the asymmetric, coplanar construction of the electrodes (23-1 and 23-2) in both the first and second prior arts, as clear from Fig. 3 and Fig. 5. Further, in the second prior art, the voltage spans both the positive and negative sides, i.e., -2.5 V to -4 V and +2.5 V to +4 V and also the voltage swing of the drive voltage is same as that of the first prior art, so the construction of the driving signal source 12 becomes difficult. If the construction is attempted to be made easier, provision may be made of an electrode for applying a separate DC voltage or the first and second optical waveguides may be made asymmetric in structure, but whatever the case, the construction becomes complicated, which makes it impractical.

[0026] The third problem, also mentioned above, was that in a high speed optical communication system, it is desired to reduce the spectral spread of the light source as much as possible and prevent the occurrence of waveform deterioration of the optical pulses caused by the spectral spread and the wavelength dispersion of the optical fibers.

[0027] Therefore, the external modulation system is advantageous in that it enables reduction of the spectral spread, but even if this system is used, there is a limit to the transmission distance at a transmission speed of over several Gbps due to the spectral spread caused by the modulation side band. Therefore, some measures are required for further improving the transmission characteristics.

[0028] The modulation system featuring the smallest spectral spread and therefore resistance to the effects of fiber wavelength dispersion uses a Mach-Zehnder interferometer type modulator. According to this system, as mentioned earlier, it is possible to reduce the spectral spread.

[0029] Therefore, in a conventional optical modulation system using a Mach-Zehnder interferometer type modulator, modulation free from frequency chirping has been performed by modulating the phases of the light propagating through the two optical waveguides of the modulator by the same magnitude in opposite directions.

[0030] However, at a transmission speed of over several Gbps, even if the frequency chirping is made zero, the deformation of the optical pulses by the spectral spread due to the modulation side band and the wavelength dispersion of optical fibers can no longer be ignored.

[0031] Therefore, there is the problem that long distance transmission is impossible in a fiber with a large fiber wavelength dispersion at a transmission speed of over several Gbps even if the spectral spread due to the modulation is reduced to the spread of just the modulation side band.

[0032] In consideration of the above-mentioned problems, the present invention provides an optical modulator which can be driven by low voltage, has a driving signal source which can be made by an integrated circuit (IC), which can suppress the offset of the driving voltage and the effects of temperature fluctuations, and which is suited to higher speed operation. With such an optical modulator, the first and second problems can be resolved.

[0033] Further, the present invention provides an optical modulator which enables long distance transmission using fibers with large fiber wavelength dispersions even at transmission speeds of over several Gbps. Using this optical modulator, it is possible to resolve the above third problem.

[0034] Figure 7 is a block diagram of the principle and constitution of an optical modulator based on the present invention. The optical modulator of the present invention basically is constructed of a Mach-Zehnder interferometer type modulator comprised of a first optical waveguide 21 and second optical waveguide 22, a first electrode 33 and second electrode 34 which cooperates with the first optical waveguide 21 and second optical waveguide 22, a driving means which imparts relative changes to the light phases of the first and second optical waveguides 21 and 22 through the first and second electrodes 33 and 34. Here, the driving means is constructed of a first driving unit 31 and second driving unit 32 which independently drive the first electrode 33 and second electrode 34. The first and second driving units 31 and 32 apply a first and second driving voltage DV_1 and DV_2 determined individually to the first and second electrodes 33 and 34.

[0035] The principle of the operation of the above-mentioned optical modulator will be clear form the explanation of the following embodiments disclosed below.

[0036] The first to eighth embodiments explained below relate in particular to the aforesaid third problem in the prior art.

[0037] Figure 8 is a view for explaining the principle of the first and later embodiments of the present invention. Figure 9 is a waveform diagram used for explaining Fig. 8.

[0038] Figure 8 shows the electric field of light at various portions of the Mach-Zehnder interferometer type modulator. In the figure, E_0 is the amplitude of the electric field of the input light CO, ω_0 is the angular frequency of the electric field of the light, t is the time, and ϕ_A and ϕ_B are the phases of the light modulated in the first and

second optical waveguides 41 and 42. Eout(t) is the electric field of the modulated light (MO). Details are given by the following equation (1).

$$\mathrm{Eout}(t) = E_0/2\{\mathrm{Cos}(\omega_0 t + \phi_A) + \mathrm{Cos}(\omega_0 t + \phi_B)\}$$
$$= E_0/2(X^2 + Y^2)^{1/2}\mathrm{Cos}\{\omega_0 t - \tan^{-1}(Y/X)\} \qquad (1)$$

where,

$$X = \mathrm{Cos}(\phi_A) + \mathrm{Cos}(\phi_B)$$

and

$$Y = \mathrm{Sin}(\phi_A) + \mathrm{Sin}(\phi_B)$$

As will be understood from the above equation (1), phase modulation of $\tan^{-1}(Y/X)$ is applied to the Eout(t). This becomes frequency chirping as shown below.

[0039] If $\omega_0 t - \tan^{-1}(Y/X)$ is set at ϕ, the angular frequency can be expressed as $\omega(t) = d\phi/dt = \omega_0 - d\{\tan^{-1}(Y/X)\}/dt$ and the wavelength can be expressed as $\lambda = 2\pi c/\omega(t)$ (where c is the speed of light). Therefore, the phase modulation of $\tan^{-1}(Y/X)$ causes fluctuation of the wavelength λ, that is, frequency chirping.

[0040] Here, the phase modulation is performed as follows.

$$\phi_A > 0,\ \phi_B < 0,\ \mathrm{ABS}(\phi_A) > \mathrm{ABS}(\phi_B)$$

$$\mathrm{ABS}(\phi_B - \phi_A) \fallingdotseq 0 \text{(light output high)}$$

$$\mathrm{ABS}(\phi_B - \phi_A) \fallingdotseq \pi \text{(light output low)}$$

where, ABS(ϕ) is the absolute value of ϕ. That is $|\phi|$.

[0041] The operational waveforms of various portions at this time are shown in Fig. 9. As shown by (f) in Fig. 9, the phase of the output light is delayed at the rising edge of the intensity of the output light and advanced at the falling edge. Corresponding to this, the center wavelength λ_0 moves to the long wavelength side at the rising edge and the short wavelength side at the falling edge, as shown by (g) in Fig. 9.

[0042] In the past, modulation was performed under the condition of $\phi_A = -\phi_B$. In this case, Eout(t) becomes as shown by equation (2):

$$\mathrm{Eout}(t) = E_0\cos(\phi)\mathrm{Cos}(\omega_0 t) \qquad (2)$$

where, $\phi = \phi_A = -\phi_B$

In this case, the amplitude of the electric field of the light is just modulated by the modulation of ϕ, and there is no fluctuation in wavelength accompanying the modulation.

[0043] By asymmetrically modulating the phase of the light of the optical waveguides 41 and 42 of the optical modulator, the center wavelength λ_0 of the modulated light is, as shown in (g) of Fig. 9, made to move to the long wavelength side at the rising edge and the short wavelength side at the falling edge.

[0044] On the other hand, the wavelength dispersion of the optical fiber is large in the case of use of a single mode optical fiber with a 1.3 μm band zero dispersion, in the 1.55 μm band, at which the smallest loss is given. The coefficient of dispersion at this time is a maximum 20 ps/nm/km. The longer the wavelength, the slower the speed of propagation through the optical fiber.

[0045] Therefore, due to the frequency chirping arising due to the principle of Fig. 8 and Fig.9 the rising edge of the optical pulse is delayed by the fiber dispersion, the falling edge is advanced, and pulse compression occurs. This works to compensate for the spread of the waveform caused by both the modulation side band and the optical fiber wavelength dispersion and acts to lengthen the transmittable optical fiber length. Pulse compression means that the pulse width is made narrower toward the center of the pulse.

[0046] In a Mach-Zehnder interferometer type modulator, as mentioned earlier, use is made of the electrooptic effect for realizing phase modulation of the light. That is, the index of refraction of a substance having an electrooptic effect is changed by the electric field by the electrode so as to change the phase of the light.

[0047] In a Mach-Zehnder interferometer type modulator, there are several methods conceivable for asymmetrically modulating each phase of the light propagating through the two optical waveguides. One is the method of modulation by driving voltages differing for the optical waveguides. The second is making the driving voltages the same, but the sectional structures of the electrodes asymmetric so as to make the application of the modulating electric fields to the optical waveguides asymmetric. The third is to change the lengths of the electrodes in the optical waveguides and thus change the lengths of the optical waveguides at which the changes in the index of refraction can be sensed.

[0048] Figure 10A is a view of the construction of a first embodiment of the present invention. In the first embodiment, the driving voltages DV_1 and DV_2 are applied asymmetrically to the electrodes 33 and 34. In the figure, the optical phase modulation in the first optical waveguide 21 is large, and the optical phase modulation in the second optical waveguide 22 is small.

[0049] Further, the first electrode 33 is comprised of the first pair of separated electrodes 33-1 and 33-2, while the second electrode 34 is comprised of the second pair of separated electrodes 34-1 and 34-2. These

are shown by hatching for easier understanding. By these pairs, a so-called travelling-wave type electrode is constructed. Between the electrodes of each pair, as illustrated, there are connected terminating resistors R. The characteristic impedances of the travelling wave type electrodes are matched. The lengths of the electrodes 33 and 34 are equal.

[0050] Figure 10B is a view of an example of the circuit of the first and second driving units. In the figure, reference numerals 51a and 51b are transistors for outputting the driving voltages DV_1 and DV_2. At the bases of these transistors are applied the data input Din. However, at one transistor side, the inverter INV is inserted. Further, constant current sources 53a and 53b are connected to the transistors. It is also possible to make the magnitudes of the currents Ia and Ib different (Ia > Ib or Ia < Ib).

[0051] Figure 11 is a time chart showing the operation of the first embodiment. DV_1 is the driving waveform for the phase modulation in optical waveguide 21, while DV_2 is the driving waveform for the phase modulation of in optical waveform 22. The polarities are reversed by DV_1 and DV_2 and the amplitude of the driving voltage made larger for DV_1, whereby the phase modulation is made asymmetric.

[0052] Looking at the position of the separated electrodes 33-1 and 34-1, the first and second optical waveguides 21 and 22 are both formed in the substrate 55, made of a Z-cut electrooptic effect crystal. Over the first and second optical waveguides 21 and 22 are overlappingly formed the driving voltage side electrodes 33-1 and 34-1 of the first and second pairs of separated electrodes 33 and 34. Alternatively, the first and second optical waveguides 21 and 22 are formed in a substrate consisting of X- or Y-cut electrooptic effect crystal. A part from the first and second optical waveguides 21 and 22 are formed the driving voltage side electrodes of the first and second pairs of separated electrodes. The plan view of this state corresponds to the case of equal lengths of the electrodes 33 and 34 in the later mentioned Fig. 13.

[0053] Figure 12 is a plan view of a second embodiment of the present invention (hereinafter, only electrodes are shown for brevity). In this embodiment, the first and second pairs of separated electrodes 33-1, 33-2 and 34-1, 34-2 have mutually different lengths. The first and second pairs of separated electrodes receive the first and second driving voltages DV_1 and DV_2 having the same levels. By this, the phase modulations of the light may be made mutually asymmetrical for the optical waveguides 21 and 22.

[0054] In the second embodiment, the first and second optical waveguides 21 and 22 are both formed in the substrate 55, made of a Z-cut electrooptic effect crystal. Over the first and second optical waveguides 21 and 22 are overlappingly formed the driving voltage side electrodes 33-1 and 34-1 of the first and second pairs of separated electrodes 33 and 34.

[0055] Figure 13 is a plan view of a third embodiment of the present invention. The first and second optical waveguides 21 and 22 are both formed in the substrate 55, made of an X- or Y-cut electrooptic effect crystal. Away from the first and second optical waveguides 21 and 22 are formed the driving voltage side electrodes 33-1 and 34-1 of the first and second pairs of separated electrodes 33 and 34.

[0056] Figure 14 is a sectional view of a fourth embodiment of the present invention. The positional relationship, when seen from a sectional view, of the first pair of separated electrodes 33 to the first optical waveguide 21 and the positional relationship, when seen from a sectional view, of the second pair of separated electrodes 34 to the second optical waveguide 22 are asymmetrical. That is, the pair of separated electrodes 34 is shifted slightly to the right in the figure.

[0057] In this case, the first and second optical waveguides 21 and 22 are both formed in the substrate 55, made of a Z-cut electrooptic effect crystal. Over the first and second optical waveguides 21 and 22 are overlappingly formed the driving voltage side electrodes 33-1 and 34-1 of the first and second pairs of separated electrodes 33 and 34. A Z-cut electrooptic effect crystal is used because the electric fields E_1 traverse the inside of the first and second optical waveguides 21 and 22 in the vertical direction.

[0058] Figure 15 is a sectional view of a fifth embodiment of the present invention. The first and second optical waveguides 21 and 22 are both formed in the substrate 55, made of an X- or Y-cut electrooptic effect crystal. Away from the first and second optical waveguides 21 and 22 are formed the driving voltage side electrodes 33-1 and 34-1 of the first and second pairs of separated electrodes 33 and 34. An X- or Y-cut electrooptic effect crystal is used because the electric fields E_1 traverse the inside of the first and second optical waveguides 21 and 22 in the horizontal direction.

[0059] Figure 16 is a sectional view of a sixth embodiment of the present invention. The optical modulator of the sixth embodiment is as follows. The first electrode 33 is constructed of a pair of separated electrodes 33-1 and 33-2 separated along the first optical waveguide 21. The second electrode 34 is formed along the second optical waveguide 22 but away from the same (22) and is grounded. One of the pair of separated electrodes, 33-1, forming the first electrode 33 receives at one end a corresponding driving voltage DV_1 and is connected at the other end to one end of the other of the pair of separated electrodes 33-2 through the terminating resistor R, the other end of the other of the pair of separated electrodes 33-2 being grounded. The separated electrode 33-1 of the driving voltage side, when viewed sectionally, is placed at an asymmetric position with respect to the first and second optical waveguides 21 and 22, and the first and second optical waveguides are formed in the substrate, constituted by an X- or Y-cut electrooptic effect crystal.

[0060] Figure 17 is a plan view of a seventh embodiment of the present invention. Figure 18 is a plan view of an eighth embodiment of the present invention.

[0061] These embodiments are constituted so that the phases of the light propagated in the first and second optical waveguides 21 and 22 become asymmetric by making the second driving voltage DV_2 always zero volt or making the second separated electrode 34 substantially not present.

[0062] In the seventh embodiment, the first and second optical waveguides 21 and 22 are formed in a substrate 55 made of a Z-cut electrooptic effect crystal, and the driving voltage side electrode 33-1 of the first pair of separated electrodes 33 is formed overlapping the first optical waveguide.

[0063] In the eighth embodiment, the first and second optical waveguides 21 and 22 are formed in a substrate 55 made of an X-cut electrooptic effect crystal, and the driving voltage side electrode 33-1 of the first pair of separated electrodes 33 is formed apart from the first optical waveguide 21.

[0064] Figure 19 is graph of the results of a first calculation for explaining the improvement in the transmission characteristics of optical fibers according to the present invention; and Fig. 20 is a graph of the results of a second calculation for explaining the improvement in the transmission characteristics of optical fibers according to the present invention.

[0065] Figure 19 shows the results of calculation of the deterioration in the minimum received light power caused by the wavelength dispersion, i.e., the power penalty. When the allowance for the power penalty caused by optical fiber transmission is 0.5 dB, the allowable wavelength dispersion in the conventional modulation method is 500 to 700 ps/nm, while when the phase modulation ratio $\phi_A:\phi_B$ is made 5:1, it is improved to 1500 ps/nm or more. Further, Fig. 20 shows the results of similar calculation by another phase modulation ratio. From this it is learned that the phase modulation ratio should be 2:1 or more.

[0066] In the above explanation, use was made of the example of the case of operation under conditions where the wavelength dispersion value changes only in the positive region (with the object of reducing the transmission loss). Therefore, the center wavelength at the rising edge of the modulated light is shifted to the long wavelength side and the center wavelength at the falling edge of the modulated light is shifted to the short wavelength side.

[0067] However, in another system using an optical fibers having other characteristics, there is a cases of operation under the conditions where the wavelength dispersion value is close to zero and also a small transmission loss is given. An optical modulator cooperating with such an optical fiber must operate not only under conditions where the wavelength dispersion is in the positive region, but also under conditions where the wavelength dispersion is in the negative region. This being the case, when the wavelength dispersion is negative, the conditions of the previously mentioned wavelength shift must be set to enable setting opposite to the aforementioned case. That is, the center wavelength at the rising edge of the modulated light is to be shifted to the short wavelength side and the center wavelength at the falling edge of the modulated to be light is to be shifted to the long wavelength side.

[0068] As explained above, according to the present invention, it is possible to halve the driving voltage compared with the past and to easily make the circuit of the driving signal source by an IC. Further, since use is made of symmetric coupled lines, it is possible to eliminate the offset of the driving voltage in the prior art and the effects of temperature fluctuations and possible to receive light signal in the receiving system without waveform deterioration. Further, as understood from the results of calculations of Fig. 19 and Fig.20, according to the present invention, the optical fiber transmission characteristics are improved over the conventional modulation system, greatly contributing to improvement of the performance of high speed optical communication apparatuses.

[0069] Reference signs in the claims are intended for better understanding and shall not limit the scope.

Claims

1. An optical modulator comprising:

    a substrate (55);
    a Mach-Zehnder interferometer having:

        an input for incoming light (CO),
        an output for outgoing light (MO), and
        first and second optical waveguides (21, 22) formed in said substrate and coupled between said input and said output; and

    an electrode structure formed on said substrate and comprising at least one pair of separated electrodes (33-1, 33-2) associated with the first optical waveguide (21) and having a driving voltage side electrode (33-1) and a ground electrode (33-2) connected thereto via a terminating resistance (R);
    the arrangement of said first and second optical waveguides and said electrode structure being asymmetric as between the first optical waveguide and the second optical waveguide for modulating the phase of light propagating through the first optical waveguide differently from the phase of light propagating through the second optical waveguide by means of the electrooptic effect.

2. An optical modulator according to claim 1, wherein

the sectional structure of the electrodes is asymmetric so as to make the application of modulating electric fields by the electrodes to the first and second optical waveguides asymmetric.

3. An optical modulator according to claim 1 or claim 2, wherein the pair of electrodes associated with the first optical waveguide (21) is a first pair (33-1, 33-2) of said electrodes, the second optical waveguide (22) has a second pair (34-1, 34-2) of such electrodes, the first and second pairs of electrodes have mutually different lengths, thus making the length of the first optical waveguide at which a change in the index of refraction of said first waveguide due to the electrooptic effect can be sensed different from the length of the second optical waveguide at which a change in the index of refraction of said second waveguide due to the electrooptic effect can be sensed.

4. An optical modulator according to claim 3, wherein the substrate (55) is a Z-cut electrooptic effect crystal, the driving voltage side electrode (33-1) of the first pair of electrodes overlaps the first optical waveguide and the driving voltage side electrode (34-1) of the second pair of electrodes overlaps the second optical waveguide.

5. An optical modulator according to claim 3, wherein the substrate (55) is an X- or a Y-cut electrooptic effect crystal and the driving voltage side electrodes (33-1, 34-1) of each of said pair of electrodes are formed away from the first and second optical waveguides, respectively.

6. An optical modulator according to claim 2, wherein the substrate (55) is a Z-cut electrooptic effect crystal, the pair of electrodes associated with the first optical waveguide (21) is a first pair (33-1, 33-2) of said electrodes, the second optical waveguide (22) has a second pair (34-1, 34-2) of such electrodes, the driving voltage side electrode (33-1) of the first pair of electrodes overlaps the first optical waveguide, the driving voltage side electrode (34-1) of the second pair of electrodes overlaps the second optical waveguide, and the positional relationship, when seen from a sectional view, of the first pair of electrodes to the first optical waveguide and the positional relationship of the second pair of electrodes to the second optical waveguide are asymmetric.

7. An optical modulator according to claim 2, wherein the substrate (55) is an X- or a Y-cut electrooptic effect crystal, the pair of electrodes associated with the first optical waveguide (21) is a first pair (33-1, 33-2) of said electrodes, the second optical waveguide (22) has a second pair of such electrodes (34-1, 34-2), the driving voltage side electrodes (33-1, 34-1) of each of said pair of electrodes are formed away from the first and second optical waveguides, respectively, and the gap between the first pair of electrodes is different from the gap between the second pair of electrodes.

8. An optical modulator according to claim 1 or claim 2, wherein the substrate (55) in an X- or a Y- cut electrooptic effect crystal, the ground electrode associated with the first optical waveguide (21) is a first ground electrode (33-2), the second optical waveguide (22) has a second ground electrode (34), the driving voltage side electrode (33-1) is positioned between the first ground electrode (33-2) and the second ground electrode (34) and is placed at an asymmetric position with respect to the first optical waveguide (21) and the second optical waveguide (22).

9. An optical modulator according to claim 2, wherein the substrate (55) is a Z-cut electrooptic effect crystal, and the driving voltage side electrode (33-1) of said pair of electrodes overlaps the first optical waveguide (21).

10. An optical modulator according to claim 2, wherein the substrate (55) is an X-cut electrooptic effect crystal, and the driving voltage side electrode (33-1) of said pair of electrodes is formed away from the first optical waveguide (21).

11. An optical modulator comprising:

a substrate (55);
a Mach-Zehnder interferometer having:

an input for incoming light (CO),
an output for outgoing light (MO), 'and
first and second optical waveguides (21, 22) formed in said substrate and coupled between said input and said output; and

an electrode structure formed on said substrate and comprising:

a first pair of separated electrodes (33-1, 33-2) associated with the first optical waveguide (21) and having a first driving voltage side electrode (33-1) and a first ground electrode (33-2) connected thereto via a first terminating resistance (R), and
a second pair of separated electrodes (34-1, 34-2) associated with the second optical waveguide (22) and having a second driving voltage side electrode (34-1) and a second ground electrode (34-2) connected thereto via a second terminating re-

sistance (R);

the arrangement of said first and second optical waveguides and said electrode structure being symmetrical as between the first optical waveguide and the second optical waveguide; and

driving means arranged to provide a first driving voltage (DV_1) to the first driving voltage side electrode (33-1) and a second driving voltage (DV_2) different from the first driving voltage to the second driving voltage side electrode (34-1) for modulating the phase of light propagating through the first optical waveguide differently from the phase of light propagating through the second optical waveguide by means of the electrooptic effect.

12. An optical modulator according to claim 11, wherein the driving means comprises:

a first driving unit (31) having a first bipolar transistor (51a) for outputting the first driving voltage (DV1) at a collector thereof in response to a data signal (D_{in}) input at a base thereof, the emitter of said first transistor being connected to a first constant current source (53a), and

a second driving unit (32) having a second bipolar transistor (51b) for outputting the second driving voltage (DV_2) at a collector thereof in response to an output from an inverter (INV) input at a base thereof, said inverter being supplied at an input thereof with said data signal (D_{in}), the emitter of said second transistor being connected to a second constant current source (53b).

13. An optical modulator according to claim 11 or claim 12, wherein the substrate (55) is a Z-cut electrooptic effect crystal, the first driving voltage side electrode (33-1) overlaps the first optical waveguide (21) and the second driving voltage side electrode (34-1) overlaps the second optical waveguide (22).

14. An optical waveguide according to claim 11 or claim 12, wherein the substrate (55) is an X- or a Y-cut electrooptic effect crystal, the first driving voltage side electroode (33-1) is formed apart from the first optical waveguide (21) and the second driving voltage side electrode (34-1) is formed apart from the second optical waveguide (22).

15. A method of modulating light comprising:

providing an optical modulator comprising:
a substrate (55);
a Mach-Zehnder interferometer having:

an input for incoming light (CO),
an output for outgoing light (MO), and
first and second optical waveguides (21, 22) formed in said substrate and coupled between said input and said output; and

an electrode structure formed on said substrate and comprising at least one pair of separated electrodes (33-1, 33-2) associated with the first optical waveguide (21) and having a driving voltage side electrode (33-1) and a ground electrode (33-2) connected thereto via a terminating resistance (R);

the arrangement of said first and second optical waveguides and said electrode structure being asymmetric as between the first optical waveguide and the second optical waveguide;

applying light to said of the Mach-Zehnder interferometer; and

providing a driving voltage to the driving voltage side electrode (33-1) of the pair of electrodes associated with the first optical waveguide (21), thereby modulating the phase of the applied light propagating through the first optical waveguide differently from the phase of the applied light propagating through the second optical waveguide by means of the electrooptic effect, even when applying the same driving voltage to an optional part of the electrode structure associated with the second optical waveguide (22).

16. A method of modulating light comprising:

providing an optical modulator comprising:
a substrate (55);
a Mach-Zehnder interferometer having:

an input for incoming light (CO),
an output for outgoing light (MO), and
first and second optical waveguides (21, 22) formed in said substrate and coupled between said input and said output; and

an electrode structure formed on said substrate and comprising:

a first pair of separated electrodes (33-1, 33-2) associated with the first optical waveguide (21) and having a first driving voltage side electrode (33-1) and a first ground electrode (33-2) connected thereto via a first terminating resistance (R), and

a second pair of separated electrodes (34-1, 34-2) associated with the second optical waveguide (22) and having a second driving voltage side electrode (34-1) and a second ground electrode (34-2) con-

nected thereto via a second terminating resistance (R) ;

the arrangement of said first and second optical waveguides and said electrode structure being symmetrical as between the first optical waveguide and the second optical waveguide; applying light to said input of the Mach-Zehnder interferometer; and
providing a first driving voltage (DV_1) to the first driving voltage side electrode (33-1) and a second driving voltage (DV_2) different from the first driving voltage to the second driving voltage side electrode (34-1), thereby modulating the phase of the applied light propagating through the first optical waveguide differently from the phase of the applied light propagating through the second optical waveguide by means of the electrooptic effect.

17. A method according to claim 16, wherein the second driving voltage (DV_2) is zero volts.

18. An optical modulator according to claim 8, wherein the sectional structure of the driving voltage side electrode (33-1) and the first optical waveguide (21) relative to the sectional structure of the driving voltage side electrode (33-1) and the second optical waveguide (22) is asymmetrical.

Patentansprüche

1. Optischer Modulator, umfassend:

ein Substrat (55);
ein Mach-Zehnder-Interferometer mit:

einem Eingang für ankommendes Licht (CO),
einem Ausgang für abgehendes Licht (MO), und
ersten und zweiten optischen Wellenleitern (21, 22), die in dem Substrat gebildet und zwischen den Eingang und den Ausgang gekoppelt sind; und

eine Elektrodenstruktur, die auf dem Substrat gebildet ist und wenigstens ein Paar von getrennten Elektroden (33-1, 33-2), die zu dem ersten optischen Wellenleiter (21) gehörten und eine ansteuerspannungs-seitige Elektrode (33-1) und eine damit über einen Abschlusswiderstand (R) verbunden Masseelektrode (33-2) aufweisen, umfasst;

wobei die Anordnung der ersten und zweiten optischen Wellenleiter und der Elektrodenstruktur zwischen dem ersten optischen Wellenleiter und dem zweiten optischen Wellenleiter asymmetrisch ist, um die Phase des Lichts, welches sich durch den ersten optischen Wellenleiter ausbreitet, unterschiedlich zu der Phase des Lichts, welches sich durch den zweiten optischen Wellenleiter ausbreitet, mit Hilfe des elektrooptischen Effekts zu modulieren.

2. Optischer Modulator nach Anspruch 1, wobei der Querschnittsaufbau der Elektroden asymmetrisch ist, um so die Anwendung von modulierenden elektrischen Feldern durch die Elektroden auf die ersten und zweiten optischen Wellenleiter asymmetrisch zu machen.

3. Optischer Modulator nach Anspruch 1 oder Anspruch 2, wobei das Paar von Elektroden, welches zu dem ersten optischen Wellenleiter (21) gehört, ein erstes Paar (33-1, 33-2) der Elektroden ist, der zweite optische Wellenleiter (22) ein zweites Paar (34-1, 34-2) von derartigen Elektroden aufweist, die ersten und zweiten Paare von Elektroden zueinander unterschiedliche Längen aufweisen, wodurch die Länge des ersten optischen Wellenleiters, an der eine Änderung im Brechungsindex des ersten Wellenleiters aufgrund des elektrooptischen Effekts erfasst werden kann, unterschiedlich zu der Länge des zweiten optischen Wellenleiters, an der eine Änderung in dem Brechungsindex des zweiten Wellenleiters aufgrund des elektrooptischen Effekts erfasst werden kann, gemacht wird.

4. Optischer Modulator nach Anspruch 3, wobei das Substrat (55) ein Z-Schnitt-Kristall mit einem elektrooptischen Effekt ist, die ansteuerspannungs-seitige Elektrode (33-1) des ersten Paars von Elektroden den ersten optischen Wellenleiter überlappt und die ansteuerspannungs-seitige Elektrode (34-1) des zweiten Paars von Elektroden den zweiten optischen Wellenleiter überlappt.

5. Optischer Modulator nach Anspruch 3, wobei das Substrat (55) ein X- oder Y-Schnitt-Kristall mit einem elektrooptischen Effekt ist und die ansteuerspannungs-seitigen Elektroden (33-1, 34-1) in jedem Paar von Elektroden getrennt von den ersten bzw. zweiten optischen Wellenleitern gebildet sind.

6. Optischer Modulator nach Anspruch 2, wobei das Substrat (55) ein Z-Schnitt-Kristall mit einem elektrooptischen Effekt ist, das Paar von Elektroden, das zu dem ersten optischen Wellenleiter (21) gehört, ein erstes Paar (33-1, 33-2) der Elektroden ist, der zweite optische Wellenleiter (22) ein zweites Paar (34-1, 34-2) von derartigen Elektroden aufweist, die ansteuerspannungs-seitige Elektrode (33-1) des ersten Paars von Elektroden den ersten

optischen Wellenleiter überlappt, die ansteuerspannungs-seitige Elektrode (34-1) des zweiten Paars von Elektroden den zweiten optischen Wellenleiter überlappt, und die Positionsbeziehung, gesehen im Querschnitt, des ersten Paars von Elektroden zu dem ersten optischen Wellenleiter und die Positionsbeziehung des zweiten Paars von Elektroden zu dem zweiten optischen Wellenleiter asymmetrisch sind.

7. Optischer Modulator nach Anspruch 2, wobei das Substrat (55) ein X- oder ein Y-Schnitt-Kristall mit einem elektrooptischen Effekt ist, das Paar von Elektroden, das zu dem ersten Wellenleiter (21) gehört, ein erstes Paar (33-1. 33-2) der Elektroden ist, der zweite optische Wellenleiter (22) ein zweites Paar von derartigen Elektroden (34-1, 34-2) aufweist, die ansteuerspannungs-seitigen Elektroden (33-1, 34-1) von jedem Paar von Elektroden getrennt von den ersten bzw. den zweiten optischen Wellenleitern gebildet sind, und der Spalt zwischen dem ersten Paar von Elektroden sich von dem Spalt zwischen dem zweiten Paar von Elektroden unterscheidet.

8. Optischer Modulator nach Anspruch 1 oder Anspruch 2, wobei das Substrat (55) ein X- oder Y-Schnitt-Kristall mit einem elektrooptischen Effekt ist, die Masseelektrode, die zu dem ersten optischen Wellenleiter (21) gehört, eine erste Masseelektrode (33-2) ist, der zweite optische Wellenleiter (22) eine zweite Masseelektrode (34) aufweist, die ansteuerspannungs-seitige Elektrode (33-1) zwischen der ersten Masseelektrode (33-2) und der zweiten Masseelektrode (34) positioniert und an einer asymmetrischen Position bezüglich des ersten optischen Wellenleiters (21) und des zweiten optischen Wellenleiters (22) platziert ist.

9. Optischer Modulator nach Anspruch 2, wobei das Substrat (55) ein Z-Schnitt-Kristall mit einem elektrooptischen Effekt ist, und die ansteuerspannungsseitige Elektrode (33-1) des zweiten Paars von Elektroden den ersten optischen Wellenleiter (21) überlappt.

10. Optischer Modulator nach Anspruch 2, wobei das Substrat (55) ein X-Schnitt-Kristall mit einem elektrooptischen Effekt ist und die ansteuerspannungsseitige Elektrode (33-1) des Paars von Elektroden weg von dem ersten optischen Wellenleiter (21) gebildet ist.

11. Optischer Modulator, umfassend:

ein Substrat (55);
ein Mach-Zehnder-Interferometer mit:

einem Eingang für ankommendes Licht (CO),
einem Ausgang für abgehendes Licht (MO), und
ersten und zweiten optischen Wellenleitern (21, 22), die in dem Substrat gebildet und zwischen den Eingang und den Ausgang gekoppelt sind; und

eine Elektrodenstruktur, die auf dem Substrat gebildet ist und umfasst:

ein erstes Paar von getrennten Elektroden (33-1, 33-2), die zu dem ersten optischen Wellenleiter (21) gehören und eine ansteuerspannungs-seitige Elektrode (33-1) und eine über einen Abschlusswiderstand (R) damit verbundene erste Masseelektrode (33-2) aufweisen, und
ein zweites Paar von getrennten Elektroden (34-1, 34-2), die zu dem zweiten optischen Wellenleiter (22) gehören und eine zweite ansteuerspannungs-seitige Elektrode (34-1) und eine damit über einen Abschlusswiderstand (R) damit verbundene zweite Masseelektrode (34-2) aufweisen:

wobei die Anordnung der ersten und zweiten optischen Wellenleiter und der Elektrodenstruktur zwischen dem ersten optischen Wellenleiter und dem zweiten optischen Wellenleiter symmetrisch ist; und eine Ansteuereinrichtung, die angeordnet ist, um eine erste Ansteuerspannung (DV_1) an der ersten ansteuerspannungs-seitigen Elektrode (33-1) und eine zweite Ansteuerspannung (DV_2), die sich von der ersten Ansteuerspannung unterscheidet, an der zweiten ansteuerspannungs-seitigen Elektrode (34-1) bereitzustellen, um die Phase des Lichts, welches sich durch den ersten optischen Wellenleiter ausbreitet, unterschiedlich zu der Phase des Lichts, welches sich durch den zweiten optischen Wellenleiter ausbreitet, mit Hilfe des elektrooptischen Effekts zu modulieren.

12. Optischer Modulator nach Anspruch 11, wobei die Ansteuereinrichtung umfasst:

eine erste Ansteuereinheit (31) mit einem ersten Bipolartransistor (51a) zum Ausgeben der ersten Ansteuerspannung (DV_1) an einem Kollektor davon im Ansprechen auf ein Datensignal (D_{in}), welches an einer Basis davon eingegeben wird, wobei der Emitter des ersten Transistors mit einer ersten Konstantstromquelle (53a) verbunden ist; und

eine zweite Ansteuereinheit (32) mit einem zweiten Bipolartransistor (51b) zum Ausgeben

der zweiten Ansteuerspannung (DV_2) an einen Kollektor davon im Ansprechen auf einen Ausgang von einem Inverter (INV), der an einer Basis davon eingegeben wird, wobei der Inverter an einem Eingang davon das Datensignal (D_{in}) erhält, und wobei der Emitter des zweiten Transistors mit einer zweiten Konstantstromquelle (53b) verbunden ist.

13. Optischer Modulator nach Anspruch 11 oder Anspruch 12, wobei das Substrat (55) ein Z-Schnitt-Kristall mit einem elektrooptischen Effekt ist, die erste ansteuerspannungs-seitige Elektrode (33-1) den ersten optischen Wellenleiter (21) überlappt und die zweite ansteuerspannungs-seitige Elektrode (34-1) den zweiten optischen Wellenleiter (22) überlappt.

14. Optischer Wellenleiter nach Anspruch 11 oder Anspruch 12, wobei das Substrat (55) ein X- oder Y-Schnitt-Kristall mit einem elektrooptischen Effekt ist, die erste ansteuerspannungs-seitige Elektrode (33-1) getrennt von dem ersten optischen Wellenleiter (21) gebildet wird und die zweite ansteuerspannungs-seitige Elektrode (34-1) getrennt von dem zweiten optischen Wellenleiter (22) gebildet wird.

15. Verfahren zum Modulieren von Licht, umfassend: Bereitstellen eines optischen Modulators, umfassend:

ein Substrat (55);
ein Mach-Zehnder-Interferometer mit:

einem Eingang für ankommendes Licht (CO),
einem Ausgang für abgehendes Licht (MO), und
ersten und zweiten optischen Wellenleitern (21, 22), die in dem Substrat gebildet und zwischen den Eingang und den Ausgang gekoppelt sind; und
eine Elektrodenstruktur, die auf dem Substrat gebildet ist und wenigstens ein Paar von getrennten Elektroden (33-1, 33-2), die zu dem ersten optischen Wellenleiter (21) gehören und eine ansteuerspannungs-seitige Elektrode (33-1) und eine damit über einen Abschlusswiderstand (R) verbundene Masseelektrode (33-2) aufweisen, umfasst;

wobei die Anordnung der ersten und zweiten optischen Wellenleiter und der Elektrodenstruktur zwischen dem ersten optischen Wellenleiter und dem zweiten optischen Wellenleiter asymmetrisch ist;

Anwenden von Licht auf das Mach-Zehnder-Interferometer; und

Bereitstellen einer Ansteuerspannung an der ansteuerspannungs-seitigen Elektrode (33-1) des Paars von Elektroden, die zu dem ersten optischen Wellenleiter (21) gehören, wodurch die Phase des angewendeten Lichts, welches sich durch den ersten optischen Wellenleiter ausbreitet, unterschiedlich zu der Phase des angewendeten Lichts, welches sich durch den zweiten optischen Wellenleiter ausbreitet, mit Hilfe des elektrooptischen Effekts moduliert wird, selbst wenn die gleiche Ansteuerspannung an einen optionalen Teil der Elektrodenstruktur, die zu dem zweiten optischen Wellenleiter gehört, angelegt wird.

16. Verfahren zum Modulieren von Licht, umfassend: Bereitstellen eines optischen Modulators, umfassend:

ein Substrat (55);
ein Mach-Zehnder-Interferometer mit:

einem Eingang für ankommendes Licht (CO),
einem Ausgang für abgehendes Licht (MO), und
ersten und zweiten optischen Wellenleitern (21, 22), die in dem Substrat gebildet und zwischen den Eingang und den Ausgang gekoppelt sind; und

eine Elektrodenstruktur, die auf dem Substrat gebildet ist und umfasst:

ein erstes Paar von getrennten Elektroden (33-1, 33-2), die zu dem ersten optischen Wellenleiter (21) gehören und eine erste ansteuerspannungs-seitige Elektrode (33-1) und eine damit über einen Abschlusswiderstand (R) verbundene erste Masseelektrode (33-2) aufweisen, und

ein zweites Paar von getrennten Elektroden (34-1, 34-2), die zu dem zweiten optischen Wellenleiter (22) gehören und eine zweite ansteuerspannungs-seitige Elektrode (34-1) und eine damit über einen zweiten Abschlusswiderstand (R) verbundene zweite Masseelektrode (34-2) aufweisen:

wobei die Anordnung der ersten und zweiten optischen Wellenleiter und der Elektrodenstruktur zwischen dem ersten optischen Wellenleiter und dem zweiten optischen Wellenleiter symmetrisch ist;

Anwenden von Licht auf den Eingang des Mach-Zehnder-Interferometers; und

Bereitstellen einer ersten Ansteuerspannung (DV_1) an der ersten ansteuerspannungs-seitigen Elektrode (33-1) und einer zweiten Ansteuerspannung (DV_2), die sich von der ersten Ansteuerspannung unterscheidet an die zweite ansteuerspannungs-seitigen Elektrode (34-1), wodurch die Phase des angelegten Lichts, welches sich durch den ersten optischen Wellenleiter ausbreitet, unterschiedlich zu der Phase des angewendeten Lichts, welches sich durch den zweiten optischen Wellenleiter ausbreitet, mit Hilfe des elektrooptischen Effekts moduliert wird.

17. Verfahren nach Anspruch 16, wobei die zweite Ansteuerspannung (DV_2) Null Volt ist.

18. Optischer Modulator nach Anspruch 8, wobei der Querschnittsaufbau der ansteuerspannungs-seitigen Elektrode (33-1) und des ersten optischen Wellenleiters (21) relativ zu dem Querschnittsaufbau der ansteuerspannungs-seitigen Elektrode (33-1) und dem zweiten optischen Wellenleiter (22) asymmetrisch ist.

Revendications

1. Modulateur optique comprenant :

un substrat (55) ;
un interféromètre de Mach-Zehnder ayant :

une entrée pour la lumière entrante (C0), une sortie pour la lumière sortante (MO), et des premier et second guides d'ondes optiques (21, 22) formés dans ledit substrat et couplés entre ladite entrée et ladite sortie ; et

une structure d'électrode formée sur ledit substrat et comprenant au moins une paire d'électrodes séparées (33-1, 33-2) associée au premier guide d'ondes optique (21) et ayant une électrode latérale de tension de commande (33-1) et une électrode de masse (33-2) raccordée à celle-ci via une résistance de terminaison (R) ;
la disposition des premier et second guides d'ondes optiques et de ladite structure optique étant asymétrique comme entre le premier guide d'ondes optique et le second guide d'ondes optique pour moduler la phase de la lumière se propageant à travers le premier guide d'ondes optique différemment de la phase de la lumière se propageant à travers le second guide d'ondes optique au moyen de l'effet électro-optique.

2. Modulateur optique selon la revendication 1, dans lequel la structure sectionnelle des électrodes est asymétrique afin de rendre asymétriques l'application des champs électriques de modulation par les électrodes aux premier et second guides d'ondes optiques.

3. Modulateur optique selon les revendications 1 ou 2, dans lequel la paire d'électrodes associée au premier guide d'ondes optique (21) dans une première paire (33-1, 33-2) desdites électrodes, le second guide d'ondes optique (22) a une seconde paire (34-1, 34-2) de ces électrodes, les première et seconde paires d'électrodes ont des longueurs mutuellement différentes, ceci rendant la longueur du premier guide d'ondes optique auquel une variation de l'indice de réfraction dudit premier guide d'ondes due à l'effet électro-optique peut être détectée, différente de la longueur du second guide d'ondes optique auquel une variation de l'indice de réfraction dudit second guide d'ondes due à l'effet électro-optique peut être détectée.

4. Modulateur optique selon la revendication 3, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en Z, l'électrode latérale de tension de commande (33-1) de la première paire d'électrodes recouvre le premier guide d'ondes optique et l'électrode latérale de tension de commande (34-1) de la seconde paire d'électrodes recouvre le second guide d'ondes optique.

5. Modulateur optique selon la revendication 3, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en X ou en Y, et les électrodes latérales de tension de commande (33-1, 34-1) de chacune de ladite paire d'électrodes sont formées séparées des premier et second guides d'ondes optiques respectivement.

6. Modulateur optique selon la revendication 2, dans lequel un substrat (55) est un substrat à effet électro-optique découpé en Z, la paire d'électrodes associée au premier guide d'ondes optique (21) est une première paire (33-1, 33-2) desdites électrodes, le second guide d'ondes (22) a une seconde paire (34-1, 34-2) de ces électrodes, l'électrode latérale de tension de commande (33-1) de la première paire d'électrodes recouvre le premier guide d'ondes optique, l'électrode latérale de tension de commande (34-1) de la seconde paire d'électrodes recouvre le second guide d'ondes optique, et la relation positionnelle, lorsqu'on regarde à partir d'une vue sectionnelle, de la première paire d'électrodes au premier guide d'ondes optique et la relation po-

sitionnelle de la seconde paire d'électrodes au second guide d'ondes optique sont asymétriques.

7. Modulateur optique selon la revendication 2, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en X ou en Y, la paire d'électrodes associée au premier guide d'ondes optique (21) est une première paire (33-1, 33-2) desdites électrodes, le second guide d'ondes optique (22) a une seconde paire de ces électrodes (34-1, 34-2), les électrodes latérales de tension de commande (33-1, 34-2), de chacune de ladite paire d'électrodes sont formées séparées des premier et second guides d'ondes optiques respectivement, et la distance entre la première paire d'électrodes est différente de la distance entre la seconde paire d'électrodes.

8. Modulateur optique selon la revendication 1 ou la revendication 2, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en X ou en Y, l'électrode de masse associée au premier guide d'ondes optique (21) est une première électrode de masse (33-2), le second guide d'ondes optique (22) a une seconde électrode de masse (34), l'électrode latérale de tension de commande (33-1) est positionnée entre la première électrode de masse (33-2) et la seconde électrode de masse (34) et est placée à une position asymétrique par rapport au premier guide d'ondes optique (21) et au second guide d'ondes optique (22).

9. Modulateur optique selon la revendication 2, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en Z, et l'électrode latérale de tension de commande (33-1) de ladite paire d'électrodes recouvre le premier guide d'ondes optique (21).

10. Modulateur optique selon la revendication 2, dans lequel le substrat (55) est un cristal à effet électro-optique découpé en X, et l'électrode latérale de tension de commande (33-1) de ladite paire d'électrodes est formée loin du premier guide d'ondes optique (21).

11. Modulateur optique comprenant :

un substrat (55) ;
un interféromètre Mach-Zehnder ayant :

une entrée pour la lumière entrante (CO), une sortie pour la lumière sortante (MO), et des premier et second guides d'ondes optiques (21, 22) formés dans ledit substrat et couplés entre ladite entrée et ladite sortie ; et

une structure d'électrode formée sur ledit substrat et comprenant :

une première paire d'électrodes séparées (33-1, 33-2) associée au premier guide d'ondes optique (21) et ayant une première électrode latérale de tension de commande (33-1) et une première électrode de masse (33-2) raccordée à celles-ci via une première résistance de terminaison (R), et une seconde paire d'électrodes séparées (34-1, 34-2) associée au second guide d'ondes optique (2) et ayant une seconde électrode latérale de tension de commande (34-1) et une seconde électrode de masse (34-2) raccordée à celles-ci via une seconde résistance de terminaison (R).

la disposition desdits premier et second guides d'ondes optiques et de ladite structure d'électrode étant symétrique comme entre le premier guide d'ondes optique et le second guide d'ondes optique ; et
un moyen de commande disposé pour fournir une première tension de commande (DV_1) à la première électrode latérale de tension de commande (33-1) et une seconde tension de commande (DV_2) différente de la première tension de commande à la seconde électrode latérale de tension de commande (34-1) pour moduler la phase de la lumière se propageant à travers le premier guide d'ondes optique différemment de la phase de la lumière se propageant à travers le second guide d'ondes optique au moyen de l'effet électro-optique.

12. Modulateur optique selon la revendication 11, dans lequel le moyen de commande comprend :

une première unité de commande (31) ayant un premier transistor bipolaire (51a) pour fournir la première tension de commande (DV_1) sur un collecteur de celui-ci, en réponse à un signal de données (D_{in}) appliqué à une base de celui-ci, l'émetteur dudit premier transistor étant raccordé à une première source de courant constant (53a), et
une seconde unité de commande (32) ayant un second transistor bipolaire (51b) pour fournir la seconde tension de commande (DV_2) à un collecteur de celui-ci en réponse à une sortie d'un inverseur (INV) appliqué à une base de celui-ci, ledit inverseur recevant sur une entrée de celui-ci, ledit signal de données (D_{in}) l'émetteur du second transistor étant raccordé à une seconde source de courant constant (53b).

13. Modulateur optique selon la revendication 11 ou la revendication 12, dans laquelle le substrat (55) est un cristal à effet électro-optique découpé en Z, la première électrode latérale de tension de comman-

de (33-1) recouvre le premier guide d'ondes optique (21) et la seconde électrode latérale de tension de commande (34-1) recouvre le second guide d'ondes optique (22).

14. Guide d'ondes optique selon la revendication 11 ou la revendication 12, dans laquelle le substrat (55) est un cristal à effet électro-optique découpé en X ou en Y, la première électrode latérale de tension de commande (33-1) est formée séparée du premier guide d'ondes optique (21) et la seconde électrode latérale de tension de commande (34-1) est formée séparée du second guide d'ondes optique (22).

15. Procédé de modulation de lumière comprenant :

la fourniture d'un modulateur optique comprenant :
un substrat (55) ;
un interféromètre de Mach-Zehnder ayant :

une entrée pour la lumière entrante (CO),
une sortie pour la lumière sortante (MO), et
des premier et second guides d'ondes optiques (21, 22) formés dans ledit substrat et couplés entre ladite entrée et ladite sortie ; et

une structure d'électrode formée sur ledit substrat et comprenant au moins une paire d'électrodes séparées (33-1, 33-2) associée au premier guide d'ondes optique (21) et ayant une électrode latérale de tension de commande (33-1) et une électrode de masse (33-2) raccordée à celle-ci via une résistance de terminaison (R) ;
la disposition desdits premier et second guides d'ondes optiques et de ladite structure d'électrode étant asymétrique comme entre le premier guide d'ondes optique et le second guide d'ondes optique ;
l'application de lumière audit interféromètre de Mach-Zehnder ; et
la fourniture d'une tension de commande à l'électrode latérale de tension de commande (33-1) de la paire d'électrodes associée au premier guide d'ondes optique (21), modulant ainsi la phase de la lumière appliquée se propageant à travers le premier guide d'ondes optique différemment de la phase de la lumière appliquée se propageant à travers le second guide d'ondes optique au moyen d'un effet électro-optique, même lors de l'application de la même tension de commande à une partie optionnelle de la structure d'électrode associée au second guide d'ondes optique (22).

16. Procédé de modulation de lumière comprenant :

la fourniture d'un modulateur optique comprenant :

un substrat (55) ;
un interféromètre de Mach-Zehner ayant :

une entrée pour la lumière entrante (CO),
une sortie pour la lumière sortante (MO), et

des premier et second guides d'ondes optiques (21, 22) formés dans ledit substrat et couplés entre ladite entrée et ladite sortie ; et

une structure d'électrode formée sur ledit substrat et comprenant :

une première paire d'électrodes séparées (33-1, 33-2) associée audit premier guide d'ondes optique (21) et ayant une première électrode latérale de tension de commande (33-1) et une première électrode de masse (33-2) raccordée à celle-ci via une première résistance de terminaison (R), et
une seconde paire d'électrodes séparées (34-1, 34-2) associée au second guide d'ondes optique (22) et ayant une seconde électrode latérale de tension de commande (34-1) et une seconde électrode de masse (34-2) raccordée à celle-ci via une seconde résistance de terminaison (R) ;
la disposition desdits premier et second guides d'ondes optiques et ladite structure d'électrode étant symétrique comme entre le premier guide d'ondes optique et le second guide d'ondes optique ;
l'application de lumière à ladite entrée de l'interféromètre de Mach-Zehnder ; et
la fourniture d'une première tension de commande (DV1) à ladite première électrode latérale de tension de commande (33-1) et d'une seconde tension de commande (DV_2) différente de la première tension de commande à la seconde électrode latérale de tension de commande (34-1), modulant ainsi la phase de la lumière appliquée se propageant à travers le premier guide d'ondes optique différemment de la phase de la lumière appliquée se propageant via le second guide d'ondes optique au moyen de l'effet électro-optique.

17. Procédé selon la revendication 16, dans lequel la seconde tension de commande (DV2) est de zéro

volt.

18. Modulateur optique selon la revendication 8, dans lequel la structure sectionnelle de l'électrode latérale de tension de commande (33-1) et le premier guide d'ondes optique (21) par rapport à la structure sectionnelle de l'électrode latérale de tension de commande (33-1) et le second guide d'ondes optique (22) est asymétrique.

Fig. 1

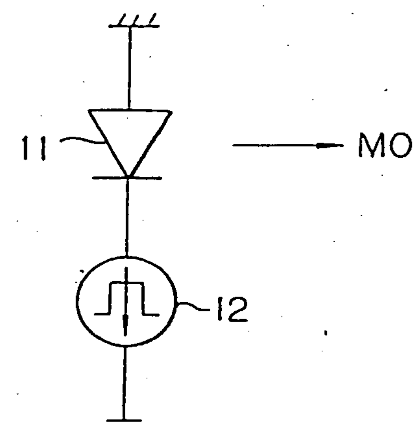


Fig. 2

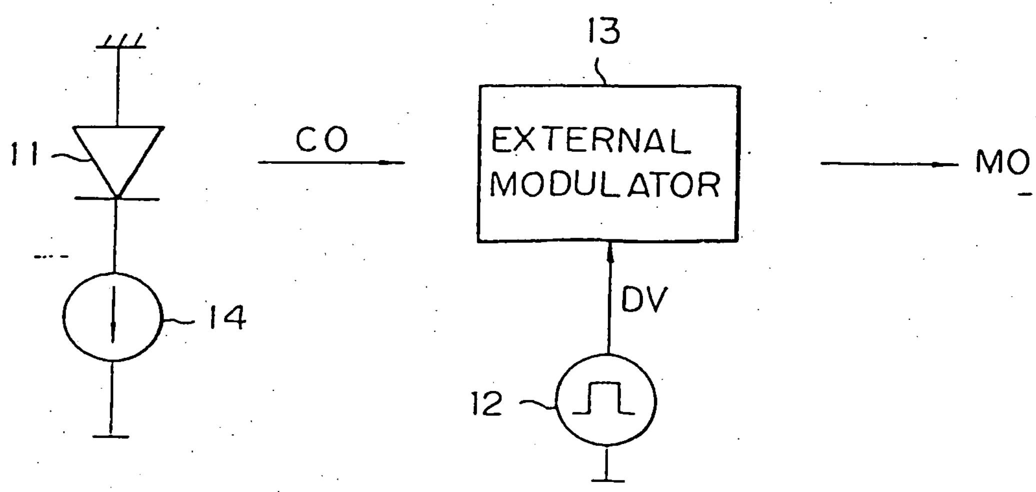
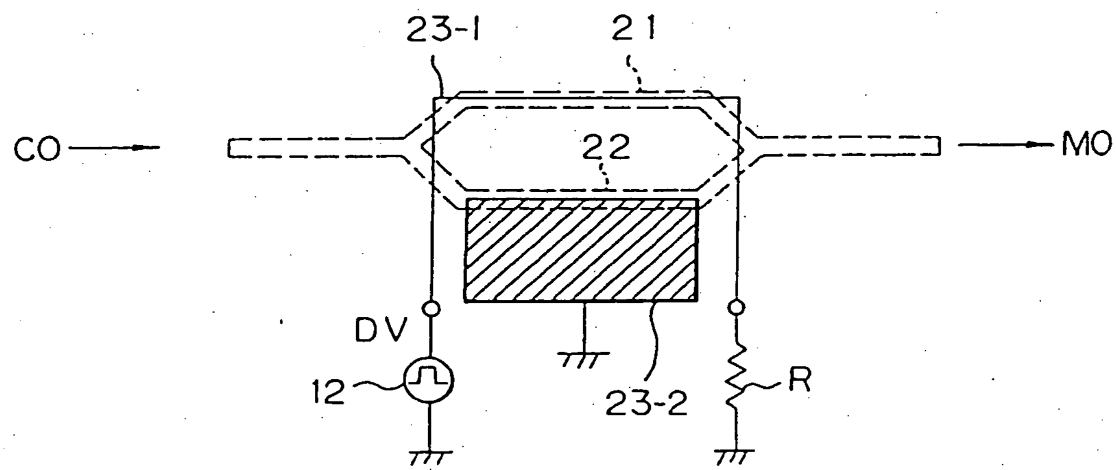


Fig. 3



THIS PAGE BLANK (USPTO)

Fig. 4

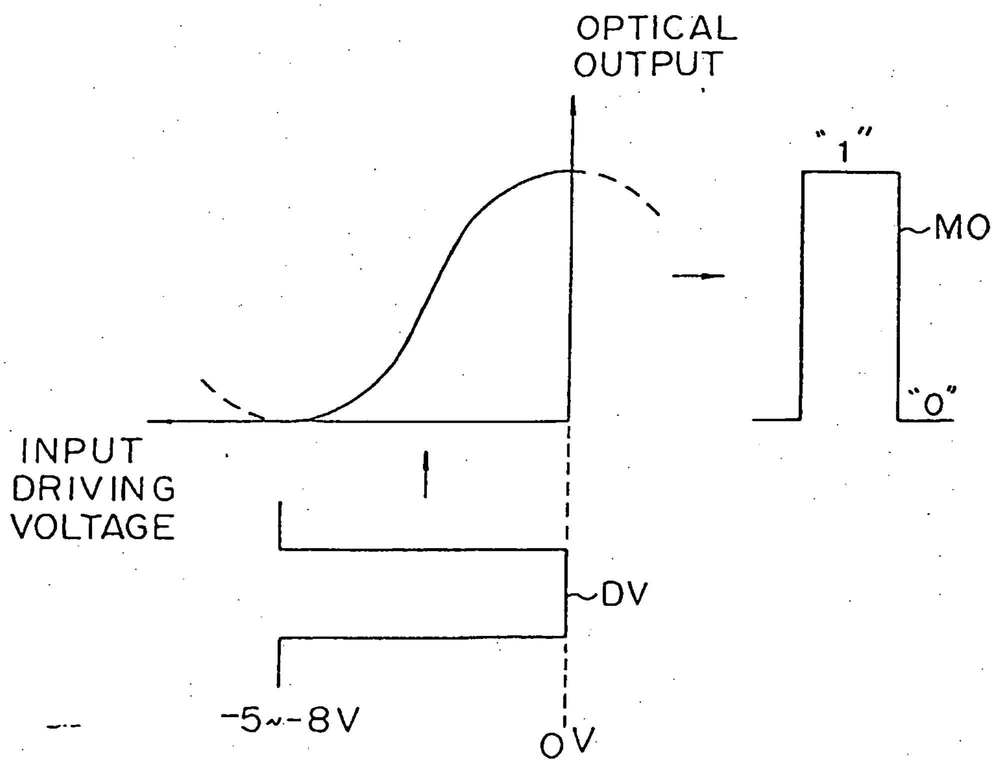


Fig. 5

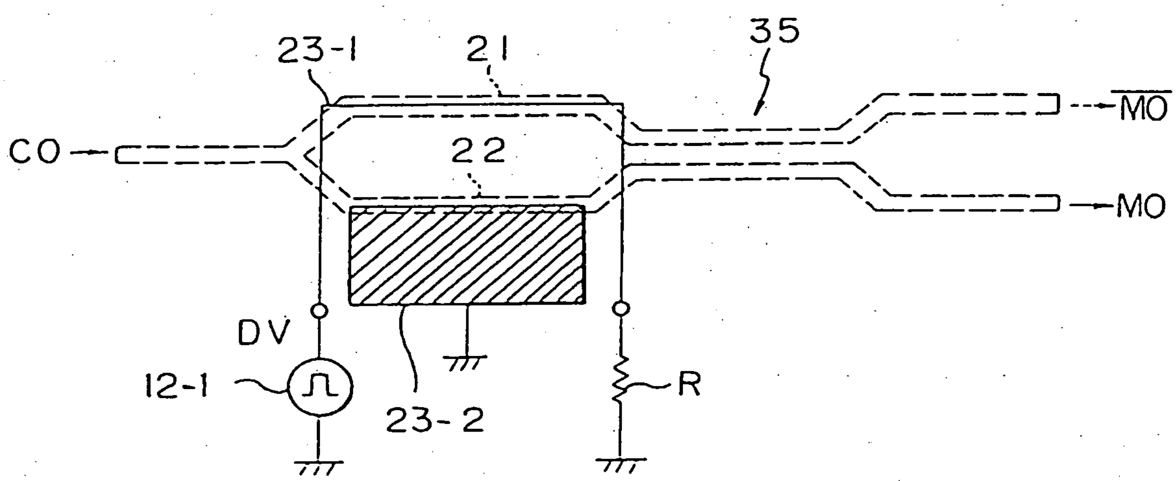
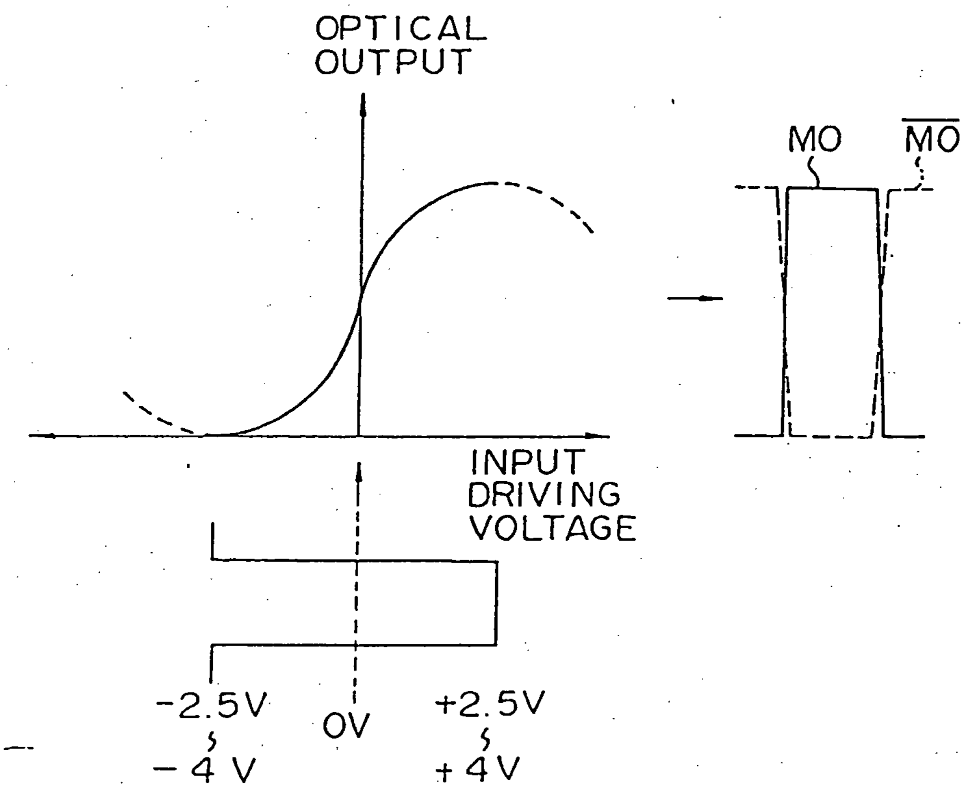


Fig. 6


OPTICAL
OUTPUT
MO
$\overline{MO}$
INPUT
DRIVING
VOLTAGE
-2.5V
~
- 4 V
0V
+2.5V
~
+ 4V

THIS PAGE BLANK (USPTO)

Fig. 7

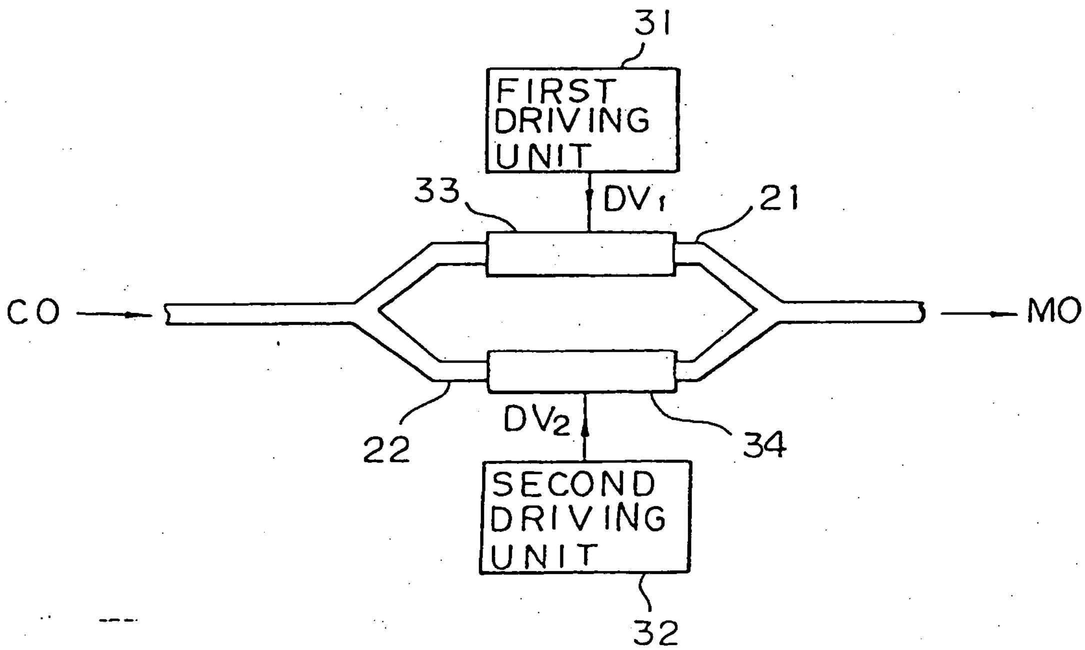

31
FIRST DRIVING UNIT
DV1
33
21
CO
MO
22
DV2
34
SECOND DRIVING UNIT
32

Fig. 8

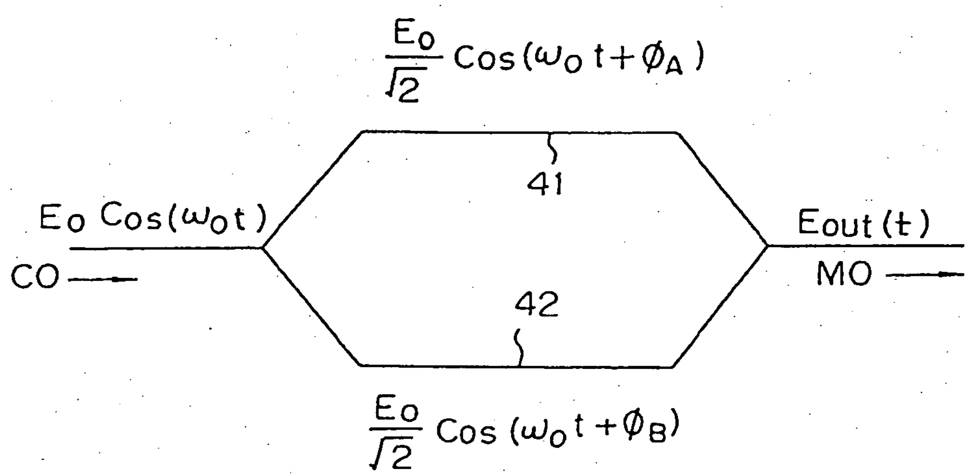
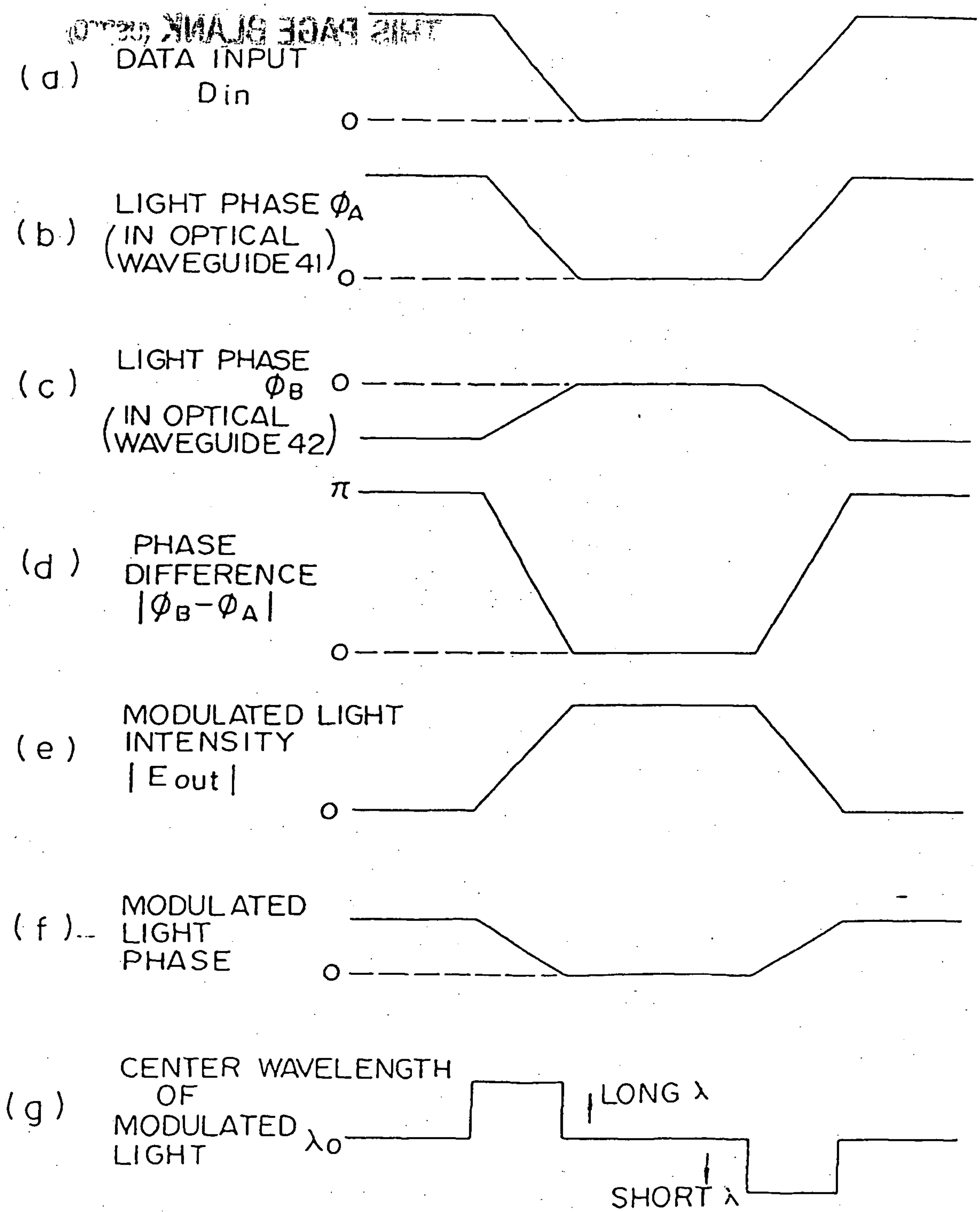

$\frac{E_0}{\sqrt{2}} \cos(\omega_0 t + \phi_A)$
41
$E_0 \cos(\omega_0 t)$
CO
42
Eout (t)
MO
$\frac{E_0}{\sqrt{2}} \cos(\omega_0 t + \phi_B)$

Fig. 9


(a)
DATA INPUT
Din
0
(b)
LIGHT PHASE ϕ_A
(IN OPTICAL WAVEGUIDE 41)
0
(c)
LIGHT PHASE ϕ_B
(IN OPTICAL WAVEGUIDE 42)
0
π
(d)
PHASE DIFFERENCE
$|\phi_B - \phi_A|$
0
(e)
MODULATED LIGHT INTENSITY
$|E_{out}|$
0
(f)
MODULATED LIGHT PHASE
0
(g)
CENTER WAVELENGTH OF MODULATED LIGHT
λ_0
LONG λ
SHORT λ

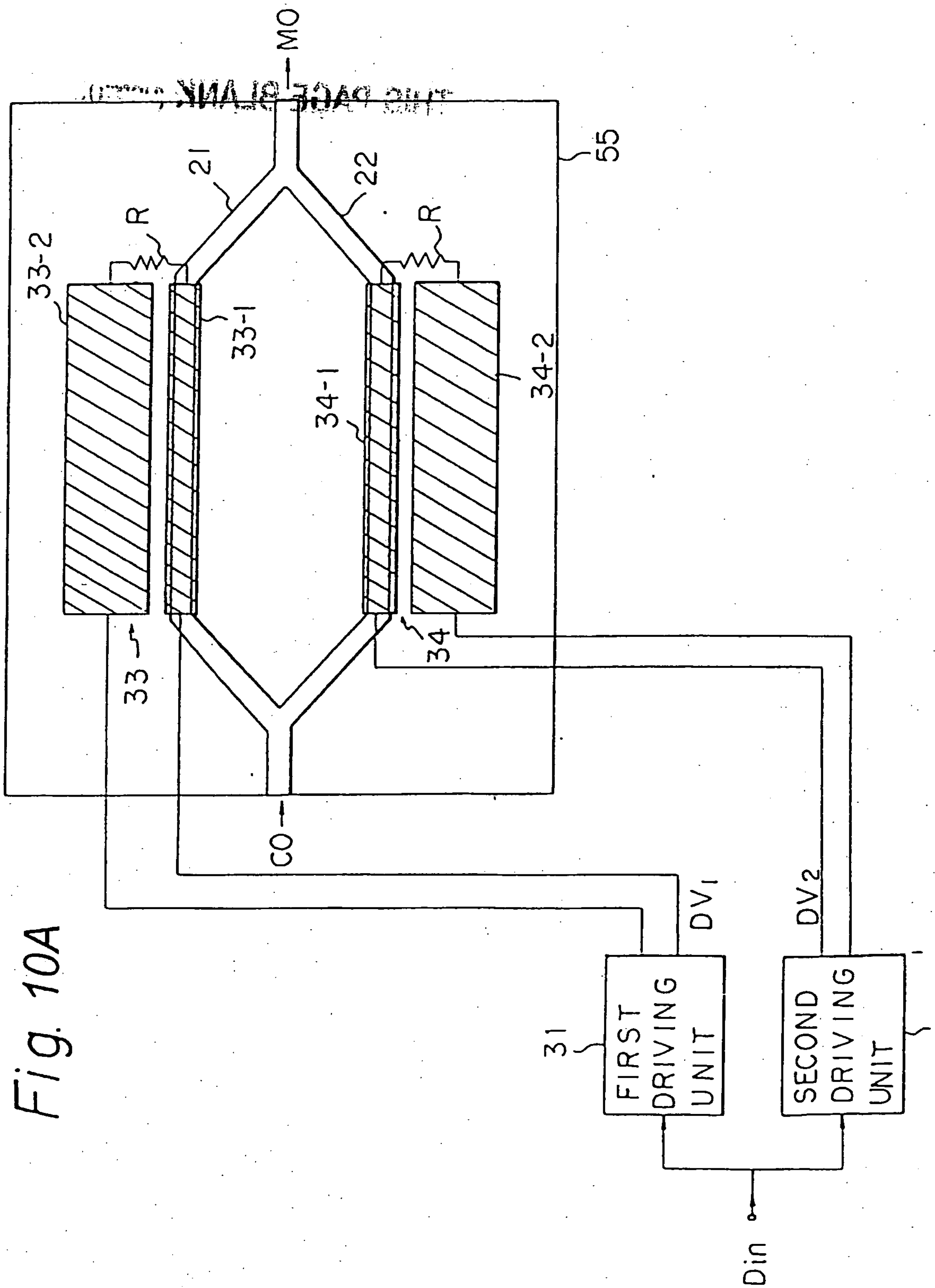
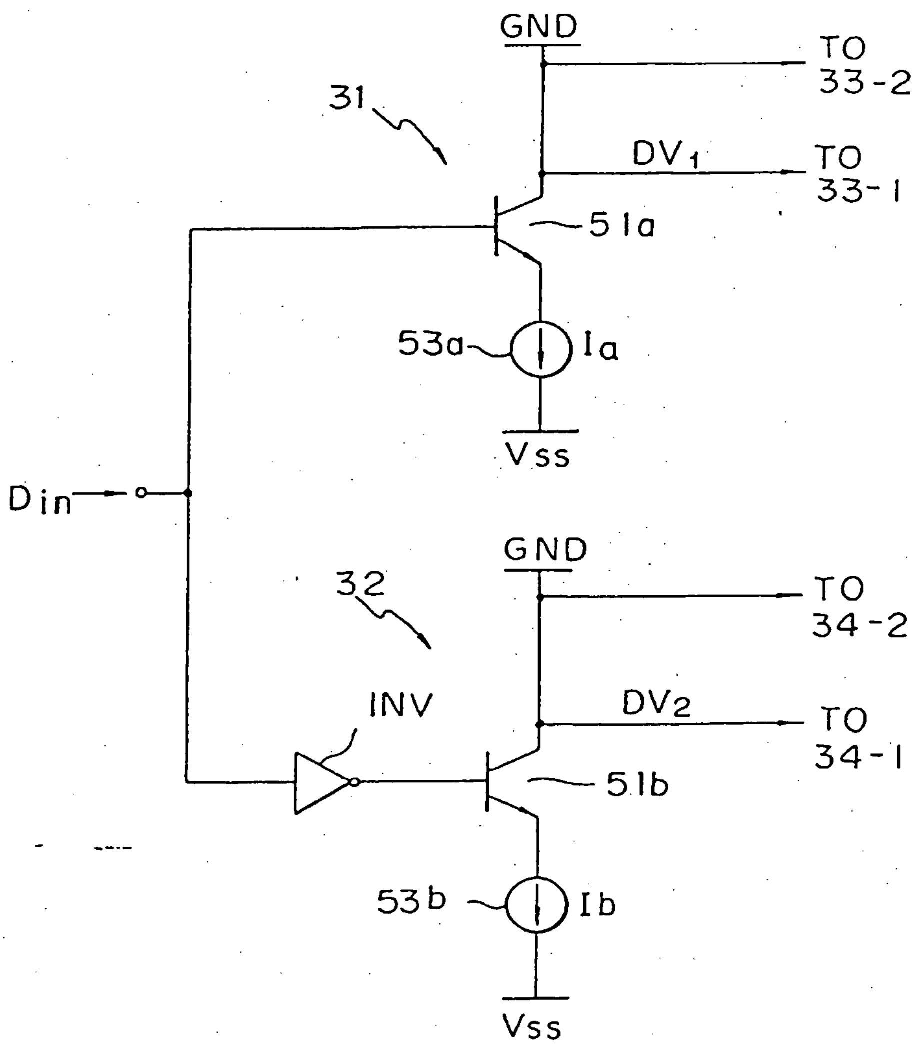

MO
55
21
22
R
R
33-2
33-1
34-1
34-2
33
34
CO
DV1
DV2
31
FIRST DRIVING UNIT
32
SECOND DRIVING UNIT
Din

Fig. 10A

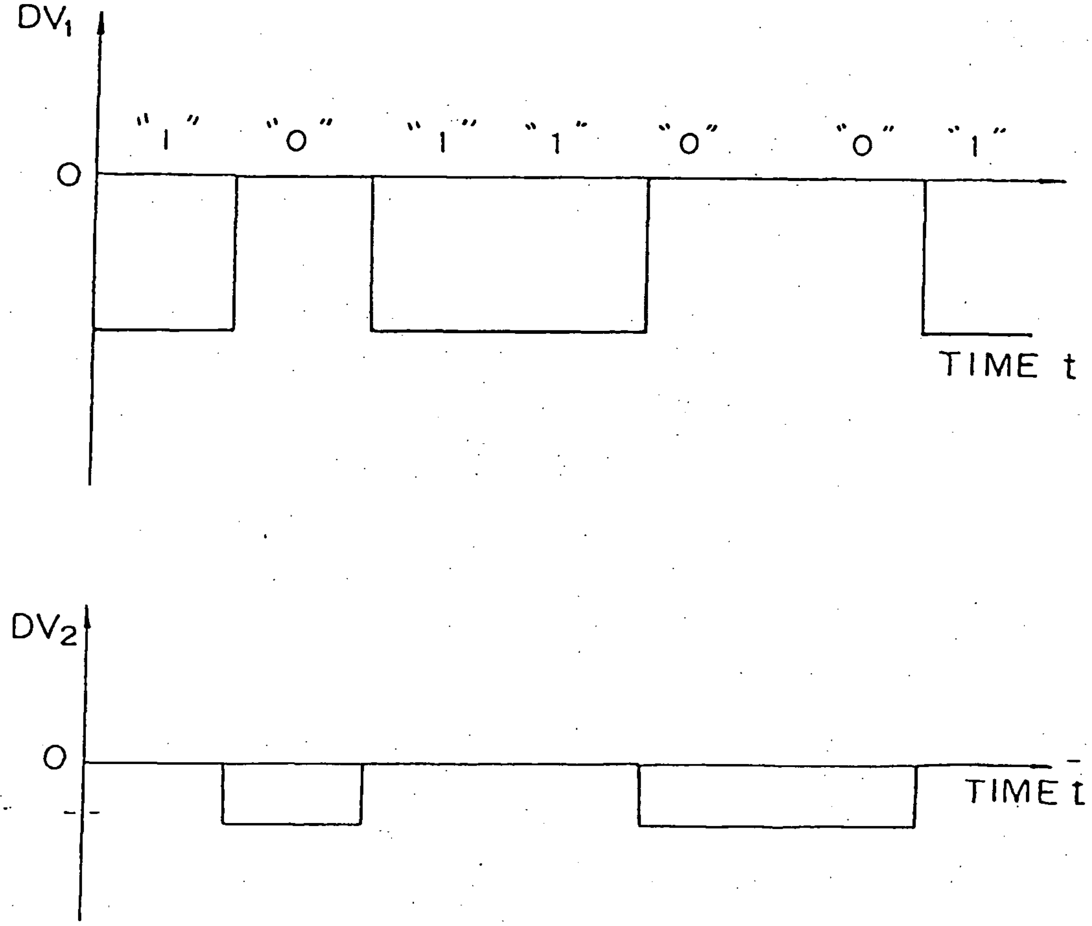
THIS PAGE BLANK (USPTO)

Fig. 10B


GND
TO 33-2
31
DV1
TO 33-1
51a
53a
Ia
Vss
Din
GND
32
TO 34-2
INV
DV2
TO 34-1
51b
53b
Ib
Vss

THIS PAGE BLANK (USPTO)

Fig. 11



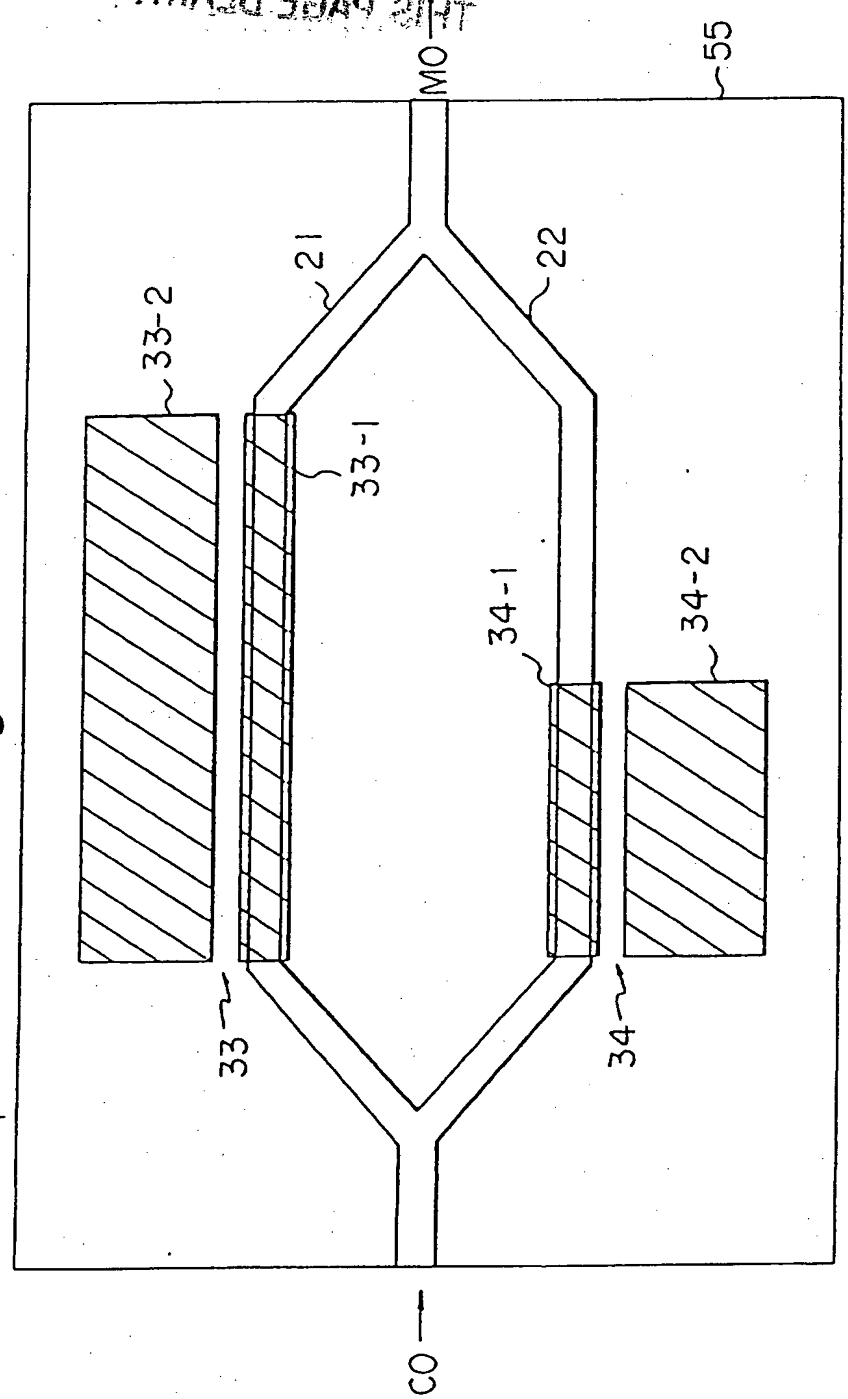


Fig. 12

Fig. 13

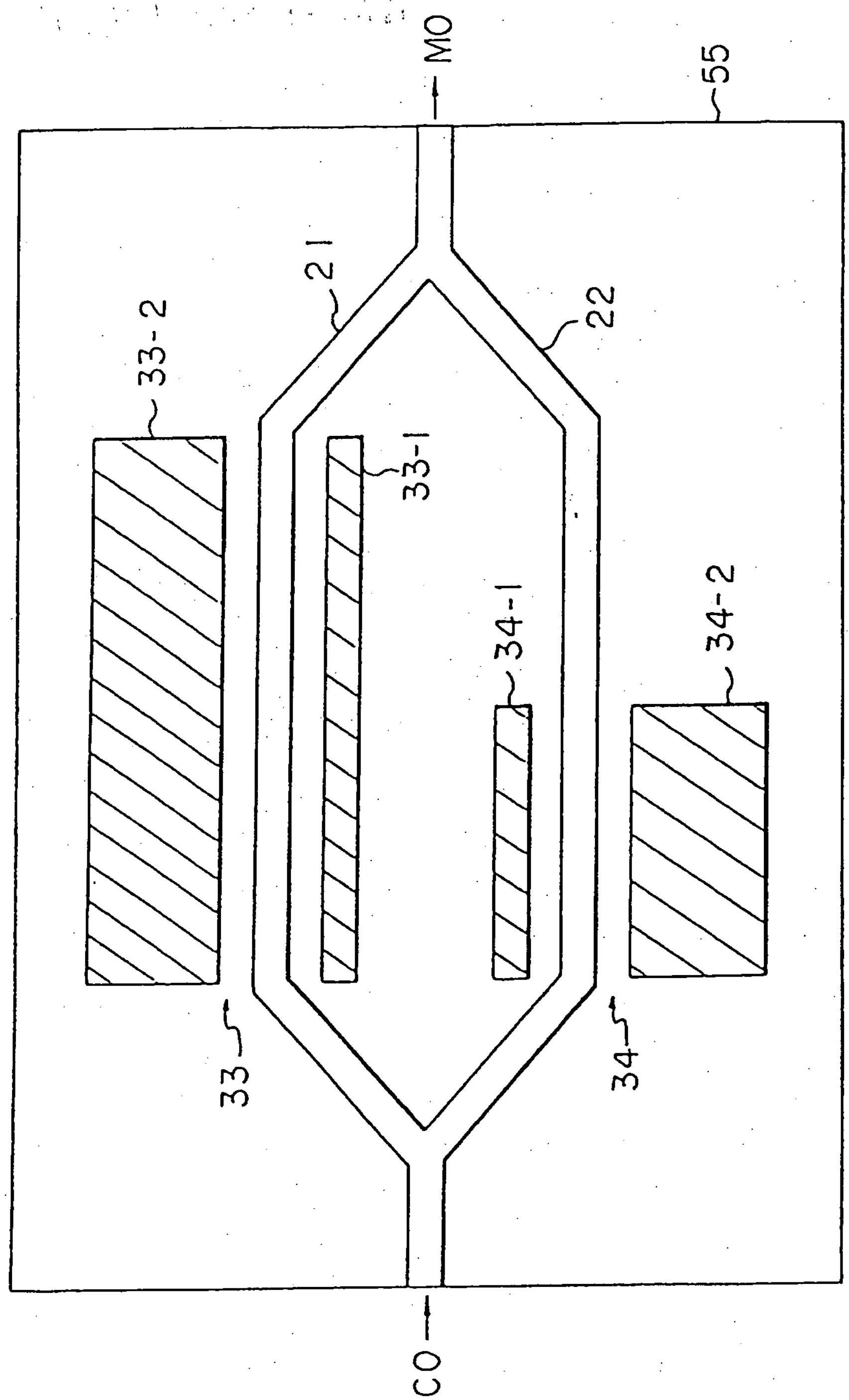


Fig. 14

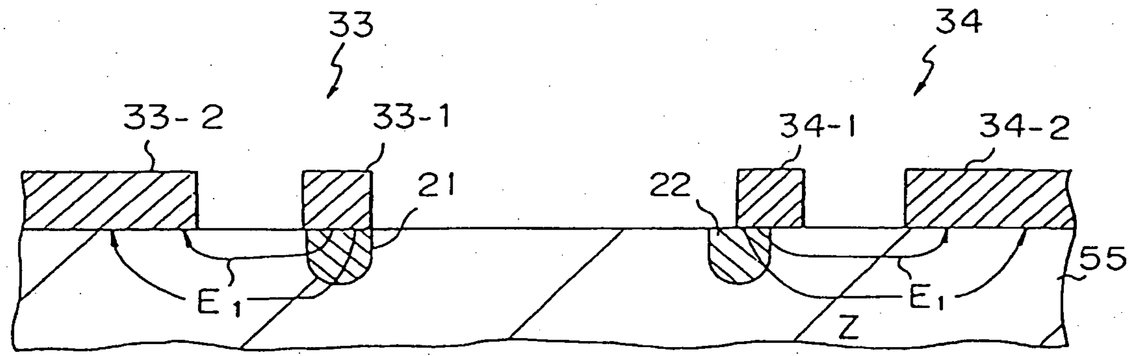


Fig. 15

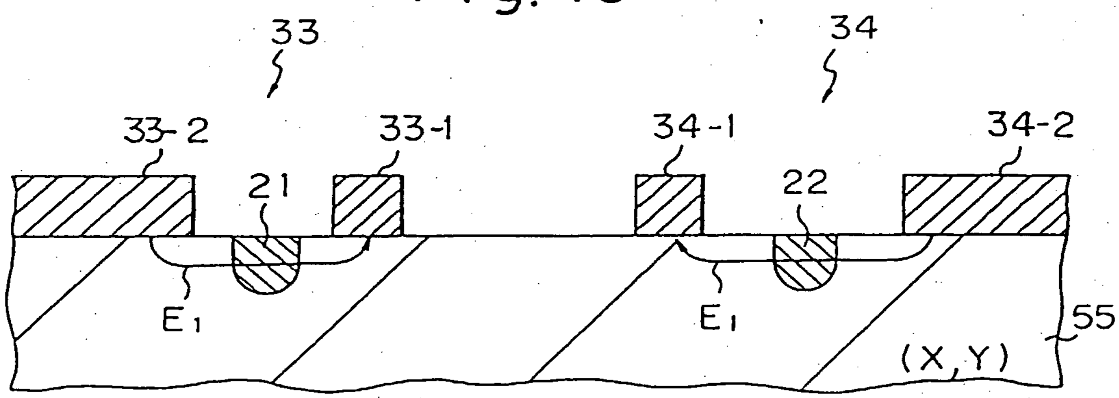


Fig. 16

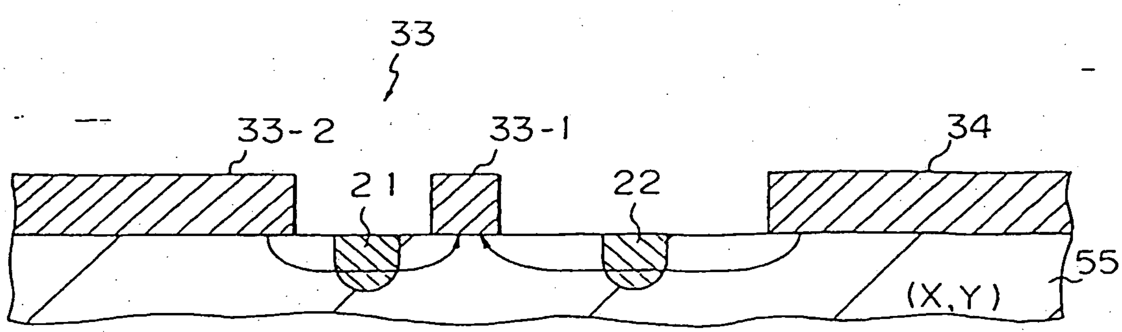
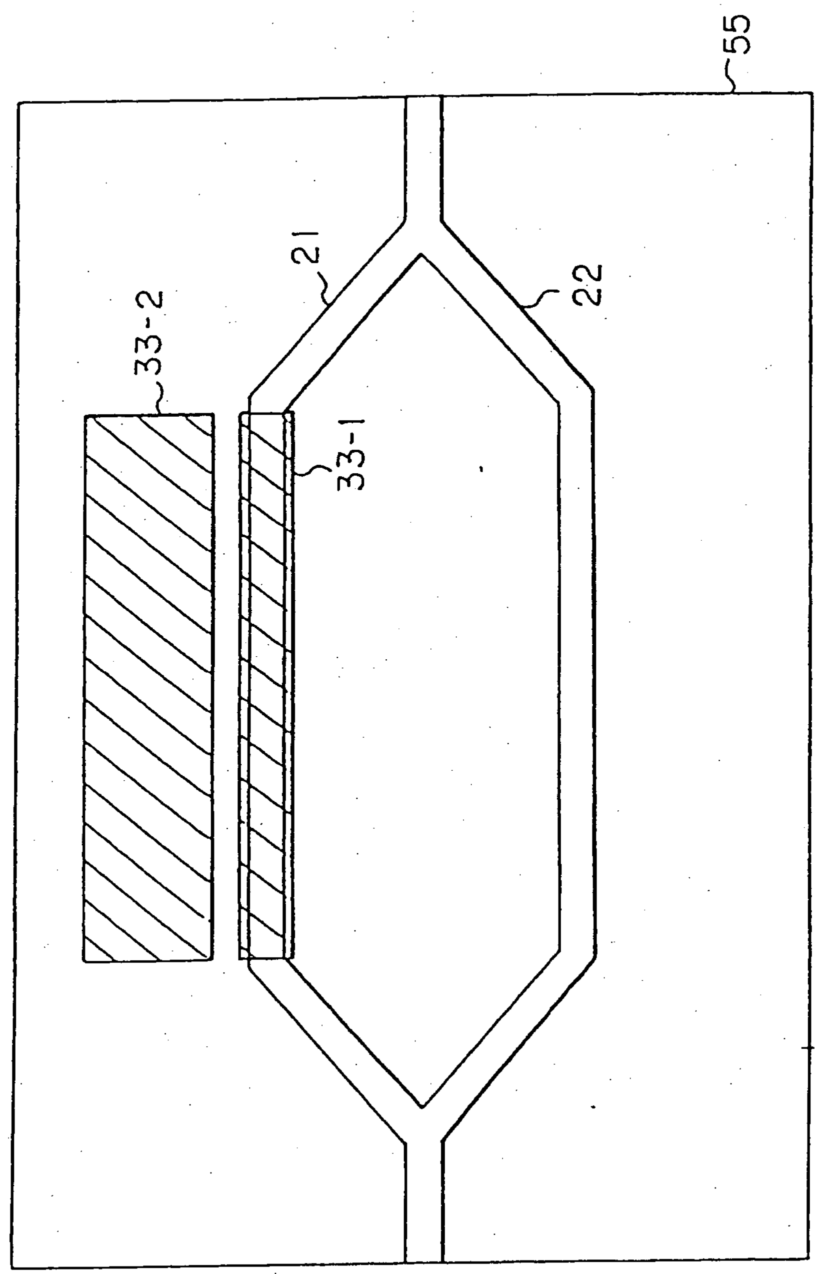


Fig. 17



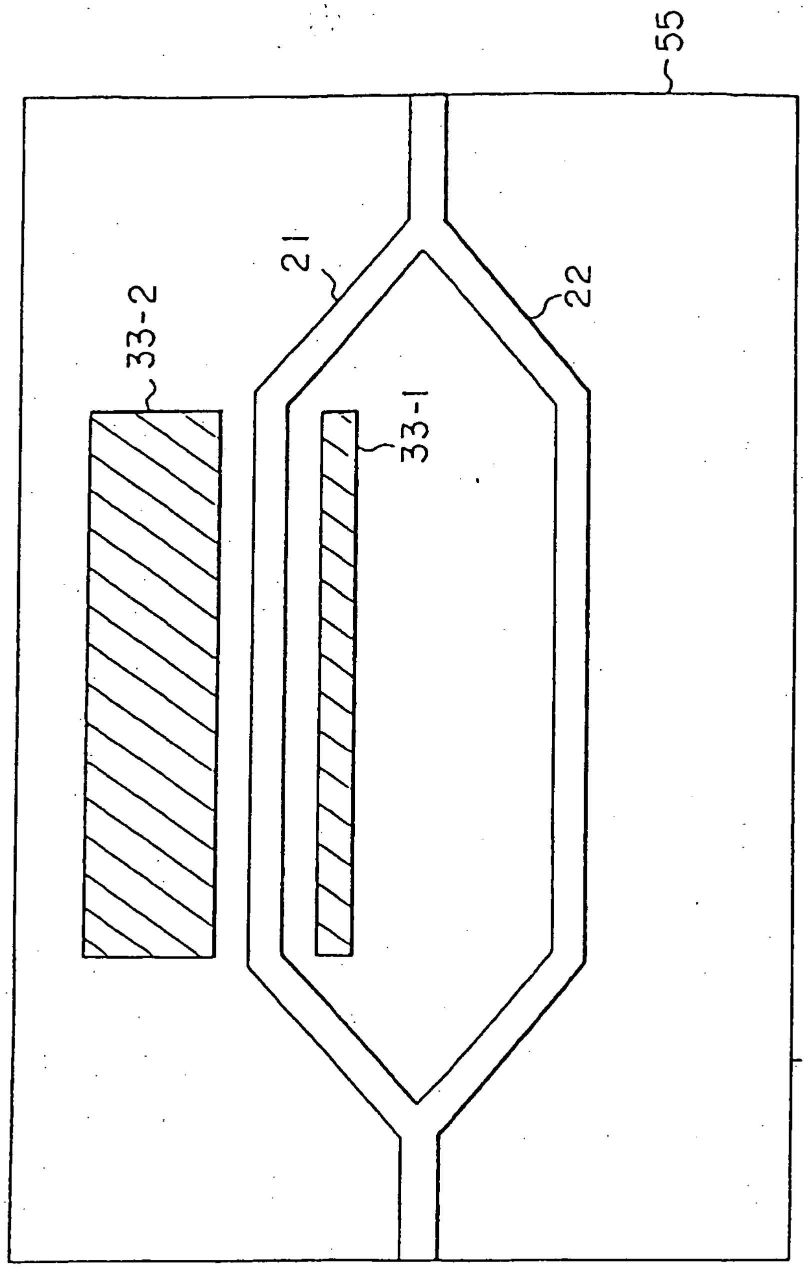


Fig. 18

Fig. 19

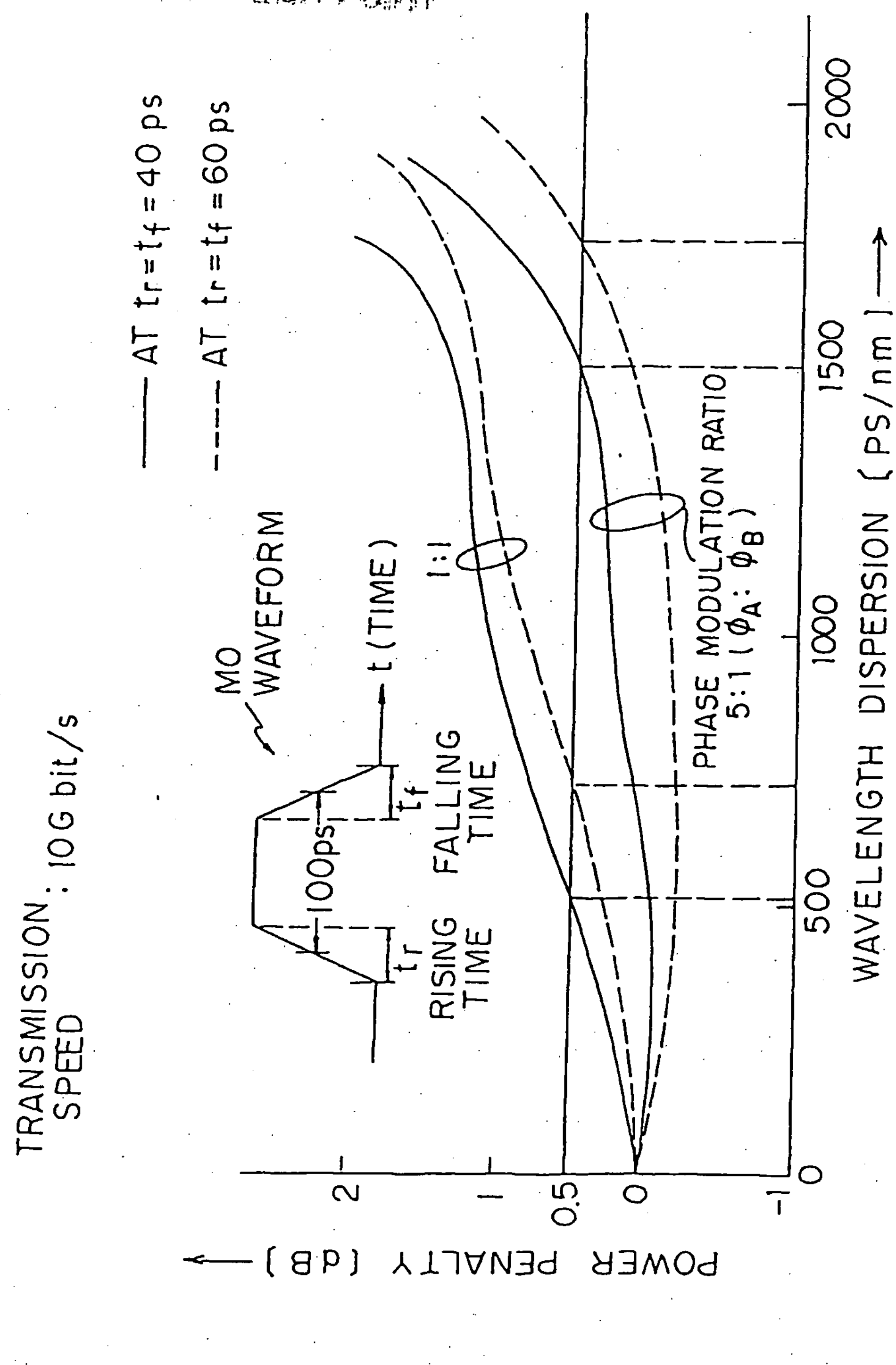
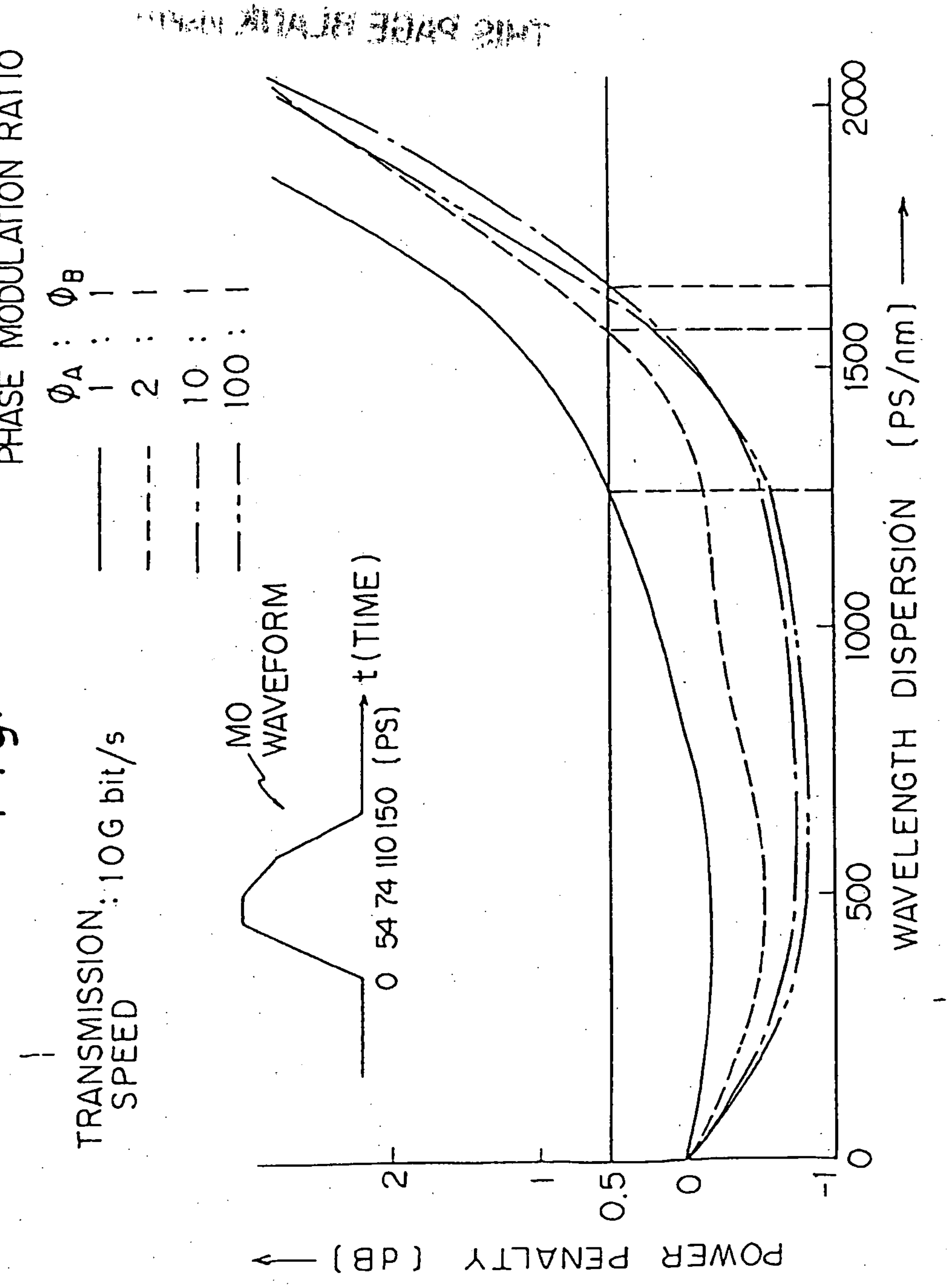

TRANSMISSION SPEED : 10G bit/s
MO WAVEFORM
t (TIME)
100ps
t_r
RISING TIME
t_f
FALLING TIME
1:1
PHASE MODULATION RATIO
5:1 (ϕ_A : ϕ_B)
—— AT $t_r = t_f = 40$ ps
- - - - AT $t_r = t_f = 60$ ps
POWER PENALTY (dB)
2
1
0.5
0
-1
0
500
1000
1500
2000
WAVELENGTH DISPERSION (PS/nm)

Fig. 20


TRANSMISSION SPEED : 10G bit/s
PHASE MODULATION RATIO
ϕ_A : ϕ_B
1 : 1
2 : 1
10 : 1
100 : 1
MO WAVEFORM
0 54 74 110 150 (PS)
t (TIME)
POWER PENALTY (dB)
2
1
0.5
0
−1
WAVELENGTH DISPERSION (PS/nm)
0
500
1000
1500
2000